The Terroir of Winter Hardiness:
Investigation of Winter Hardiness, Water Metrics, and Yield of Riesling and Cabernet Franc in the Niagara Region Using Geomatic Technologies

By

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Abstract

Grapevine winter hardiness is a key factor in vineyard success in many cool climate wine regions. Winter hardiness may be governed by a myriad of factors in addition to extreme weather conditions – e.g. soil factors (texture, chemical composition, moisture, drainage), vine water status, and yield– that are unique to each site. It was hypothesized that winter hardiness would be influenced by certain *terroir* factors , specifically that vines with low water status [more negative leaf water potential (leaf ψ)] would be more winter hardy than vines with high water status (more positive leaf ψ). Twelve different vineyard blocks (six each of Riesling and Cabernet franc) throughout the Niagara Region in Ontario, Canada were chosen. Data were collected during the growing season (soil moisture, leaf ψ), at harvest (yield components, berry composition), and during the winter (bud $LT_{50,}$ bud survival). Interpolation and mapping of the variables was completed using ArcGIS 10.1 (ESRI, Redlands, CA) and statistical analyses (Pearson's correlation, principal component analysis, multilinear regression) were performed using XLSTAT. Clear spatial trends were observed in each vineyard for soil moisture, leaf ψ, yield components, berry composition, and LT_{50}. Both leaf ψ and berry weight could predict the LT_{50} value, with strong positive correlations being observed between LT_{50} and leaf ψ values in eight of the 12 vineyard blocks. In addition, vineyards in different appellations showed many similarities (Niagara Lakeshore, Lincoln Lakeshore, Four Mile Creek, Beamsville Bench). These results suggest that there is a spatial component to winter injury, as with other aspects of *terroir*, in the Niagara region.

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Introduction and Hypotheses

From the hot, dry conditions in the vineyards of British Columbia to the maritime climate of Nova Scotia, Canada's wine regions are unique in the wine world. Of all the provinces now making wine, the Niagara wine region is the most productive (Wine Council of Ontario 2011). Although initially planted with hybrid varieties, the Niagara region is now predominantly growing *Vitis vinifera* cultivars such as Chardonnay, Gewurztraminer, Riesling, Pinot noir, and Cabernet franc (Shaw 2005). Unlike many wine regions planted with these cultivars, Niagara often has to contend with lethally cold temperatures during the winter months that can threaten their viability.

Like many woody plants, grapevines are able to survive sub-zero temperatures with considerable success. This ability to withstand winter temperatures is also known as winter hardiness and is a key factor in the survival of vineyards in Northern latitudes. Winter hardiness is achieved by a process called cold acclimation which begins to develop in woody plants upon the onset of shorter days and cooler night-time temperatures (Schnabel and Wample 1987). Winter hardiness, like many other vine characteristics, is governed by the *terroir* of a vineyard. *Terroir*, a term that encompasses the environmental and vine-based characteristics of a vineyard, is well defined in older wine regions of the world (Reynolds et al. 2007, van Leeuwen and Seguin 2006). However, through precision viticulture, Geographic information system (GIS) techniques, and wine-making practices, efforts are now being made to elucidate the *terroir* of New World wine regions such as those in Australia, the United States, and Canada (Bramley and Hamilton 2004, Gillerman et al. 2006, Reynolds et al. 2007).

Geographic information systems are computer-based programs which allow for the presentation of geographic information with a high degree of resolution and accuracy (Vaudour 2002). Geographic information systems research has become an important aspect in many areas of science. In recent years, its use within viticultural studies has increased dramatically. Work done with GIS and mapping programs has allowed for the spatial analysis of important vineyard characteristics such as soil composition, yield components, and water status (Bramley et al. 2011, Gillerman et al. 2006, Reynolds et al. 2007).

One of the most highly studied aspects of *terroir* is water availability (soil moisture) and vine water status. Vine water status, in particular, has been continuously linked to many other vine and berry characteristics such as vigour, berry weight, and anthocyanin and phenol concentrations (Koundouras et al. 2006, Matthews and Nuzzo 2007, van Leeuwen and Seguin 2006). It is a measure of water use by the plant, with high leaf ψ (low water stress) having values of approximately -7.0 bars and low leaf ψ (high water stress) resulting in values as low as -18 bars (Williams and Araujo 2002). Grape yield is also an important factor in viticulture which, like winter hardiness, is drastically changed by vineyard conditions. Effects of yield on berry composition are documented as well, with high yields often being associated with low berry quality (Seguin 1986). However, there are no clear relationships established between winter hardiness and water status metrics (soil moisture and leaf ψ), yield components, or fruit composition. Additionally, the impact of spatial variability on winter hardiness and these other vineyard components is not known.

The objective of this project was to use geomatic tools such as Global Positioning Systems (GPS) and GIS to investigate winter hardiness of two widely planted varieties in the Niagara region - Riesling and Cabernet franc - and determine its relationship to water availability, vine water status, and yield components. It was hypothesized that winter hardiness would be spatially correlated with soil moisture, leaf ψ, and yield variations and that plants which were water stressed during the summer months would be more winter hardy than vines with more water available to them. Further relationships were hypothesized to occur between bud LT_{50} (temperature at which 50% of buds die) values and fruit composition and vine size, supporting the relationships between hardiness and water metrics. Additionally, it was hypothesized that water metrics and yield components would be related to fruit composition and that water metrics, yield, and bud LT_{50} would display temporally stable spatial trends.

Chapter 1: Literature Review

1.1 The process of cold acclimation and winter hardiness in woody plants and grapevines

1.1.1 Winter injury

The continental climates of the world can be unforgiving places for many organisms, including plants. From hot, dry summers to bitterly cold winters plant species must adapt to survive all possible conditions. As temperatures fall below zero, water within the plant becomes its enemy. Damage is imminent when water molecules begin to form homogenous nuclei – clusters of molecules that are ice-like in structure (Wolfe and Bryant 1999). If these clusters remain energetically favourable then ice can rapidly form in the apoplast (extracellular ice) and symplast (intracellular ice) of plant cells, causing freezing and damage to cellular structures, and eventually cell death (Burke et al. 1976, Wolfe and Bryant 1999).

Most often, extracellular ice causes a drastic drop in osmotic potential outside of a plant cell. This draws water out of the cell, leading to cellular dehydration and cell membrane injury (Burke et al. 1976, Fennell 2004, Fitter and Hay 2002, Lenne et al. 2010, Nagao et al. 2006, Purves et al. 2003, Xin and Browse 2000). Extracellular ice is followed by rapid intracellular ice formation, freezing all the components within the cell, causing anaerobic stress, dehydration, membrane destruction, cell rupture, and death (Burke et al. 1976, Fennell 2004, Fitter and Hay 2002, Mills et al. 2006, Purves et al. 2003, Zabadal et al. 2007). On a larger scale, ice formation can also cause considerable splitting and shearing of important tissues such as bark, xylem, and phloem (Burke et al. 1976). Injuries of this scale can leave the plant prone to infections (Fennell 2004).

The type of damage described above can occur in every part of the plant when exposed to freezing temperatures. This is known as winter injury or freeze damage and is not just associated with absolute temperature but overall weather conditions and temperature fluctuations from late fall to early spring (Lisek 2007, Scagel et al. 2010, Zabadal et al. 2007). Alongside relatively short growing seasons, freeze damage is the most limiting factor to plant growth and distribution in continental climates (Burke 1976). This includes both inter-species and intra-species variations in distribution among woody plants (Lenne et al. 2010, Lisek 2007). Grapevine cultivars are a good example of this since most commercial cultivars of *Vitis vinifera* cannot survive climates that reach below -23 ^{o}C to -25 ^{o}C (Fennell 2004, Jones et al. 2000, Shaw 2005). In contrast, American and French-American hybrids show little damage even at temperatures below -30 ^{o}C (Clore et al. 1974, Fennell 2004, Zabadal et al. 2007).

For grapevines, the wintering bud is most susceptible to winter injury, followed by the canes and trunk (Fennell 2004, Hamman et al. 1990, Schnabel and Wample 1987). Buds are more susceptible to winter injury at the tips of canes where more water is present (Fennell 2004, Wolpert and Howell 1984). However, basal buds can also be sensitive on poorly developed canes (Wolpert and Howell 1984). Primary (fruiting) buds are also less cold hardy than secondary or tertiary buds within the terminal bud structure (Edgerton and Shaulis 1953, Fennell 2004, Howell et al. 1978, Zabadal et al. 2007). Fruiting buds of most commercial cultivars can survive temperatures around -20 ^{o}C before bud death (Hamman 1996, Lisek 2007, Mills et al. 2006, Wolf and Cook 1994). Their relative fragility can have implications on fruit quality and yield during the growing season. If protective measures are not implemented, not just buds but whole canes, trunks, or vines can die, leading to considerable yield losses for years after (Fennell 2004, Ferguson et al. 2011, Jones et al. 2000, Keller and Mills 2007, Zabadal et al. 2007). However, vines can achieve considerable cold tolerance by becoming dormant and by undergoing a process known as cold acclimation.

1.1.2 The process of cold acclimation and dormancy

When temperatures begin to dip in continental climates in the fall, cold hardy plants - which can range from mosses, to cereals, to trees and grapevines - have already begun a phenomenon known as cold acclimation (Lavee and May 1997, Nagao et al. 2006). Taking approximately three weeks, cold acclimation is a process by which a plant becomes winter hardy (Burke et al. 1976, Koster and Lynch 1991, Sauter et al. 1996). Concurrent with cold acclimation, plants also enter a state of winter dormancy - a reduction or temporary cessation of growth (Arora et al. 2003, Campoy et al. 2011, Lavee and May 1997, Xin and Browse 2000, Zhang et al. 2011). Both processes differ in execution (and extent) between species and cultivars.

Winter dormancy and cold acclimation begin long before the first signs of frost. In fact, grapevines begin preparing for the winter season in late summer. It is at this point that shoot maturation and periderm development begins, triggered by the shortening day lengths after the summer solstice (Arora et al. 2003, Fennell 2004, Howell and Shaulis 1980, Keller 2010, Keller and Mills 2007, Lavee and May 1997, Mullins et al. 1996). Shorter day length (a decrease in photoperiod) is the most important environmental cue for both dormancy and cold acclimation (Arora et al. 2003, Berrocal-Lobo et al. 2011, Campoy et al. 2011, Fitter and Hay 2002, Keller 2010, Kramer 1923, Schnabel and Wample 1987). Dormancy can be fully reached with shorter photoperiods alone (Fennell 2004, Ferguson et al. 2011, Kramer 1923, Raghavendra 1991, Xin and Browse 2000). However, in order to reach full winter hardiness through cold acclimation, vines must be continuously subjected to colder temperatures (Arora et al. 2003, Berrocal-Lobo et al. 2011, Bohn et al. 2007, Fennell 2004, Ferguson et al. 2011, Gusta et al. 2005, Keller 2010, Schnabel and Wample 1987). Maximum hardiness is achieved in grapevines by mid-winter, once temperatures are consistently at or below -5 ^{o}C, and is maintained until March (Basinger and Hellman 2006, Keller 2010, Wolf and Cook 1992). It is the cold acclimation process which protects the vine from winter damage.

Once winter hardy, the vine and its buds are not only resistant to low temperature stresses, but also those associated with dehydration as well (Fennell 2004, Nagao et al. 2006, Sauter et al. 1996). In fact, a state of dehydration is self-imposed by the plant as part of the process (Burke et al. 1976, Mullins et al. 1996, Sauter et al. 1996, Xin and Browse 2000, Zabadal et al. 2007). Total water content within the plant can decrease from 80 % to approximately 50 % between the growing season and the onset of winter (Fennell 2004, Keller 2010, Lavee and May 1997). This is an important physiological change since it has been shown that a decrease in water content leads to an increase in hardiness (Burke et al. 1976, Fennell 2004, Kalberer et al. 2006, Wolpert and Howell 1984). Other changes within the plant include increases and decreases in various hormones, and accumulation of various cryoprotectants such as sugars, lipids, and proteins (Arora et al. 2003, Fitter and Hay 2002, Keller 2010, Scagel et al. 2010, Xin and Browse 2000).

During cold acclimation, growth inhibiting hormones, such as abscisic acid (ABA), are slowly overtaking growth promoting hormones, such as gibberellic acid (GA), auxins, and cytokinins (Lavee and May 1997). This promotes growth cessation, periderm formation, leaf abscission, and the movement of important storage compounds out of the leaves and into more permanent organs of the plant (Fitter and Hay 2002, Keller 2010, Zhang et al. 2011). Abscisic acid in particular has been the subject of many scientific studies due to its importance in dormancy induction and increased carbohydrate accumulation (Bohn et al. 2007, Gusta et al. 2005, Keller 2010, Kovacs et al. 2011, Lambers et al. 2008, Nagao et al. 2006, Olinevich et al. 2000, Takezawa et al. 2011, Zhang et al. 2011).

Carbohydrates, in the form of starch and various sugars, accumulate in winter hardy plants with leaf abscission (Howell et al. 1978, Keller 2010, Lavee and May 1997, Zabadal et al. 2007). Starch is broken down to produce smaller sub-units of mono-, di-, and oligosaccharides. Therefore, as sugar concentrations increase in plants, starch concentrations decrease (Ashworth et al. 1993, Fennell 2004, Keller 2010, Nagao et al. 2006, Sauter et al. 1996). The concentration of sugars increases greatly within winter plants due to this process. For example, in puma rye, sugar concentrations increase from 10.3 mg/g to 24.7 mg/g during acclimation (Koster and Lynch 1991). This coincides with an overall increase in hardiness and freeze tolerance (Ashworth et al. 1993, Gusta et al 2005, Keller 2010, Lambers et al. 2008, Mullins et al. 1996). However, total sugar concentration does not show good correlation with winter hardiness (Hamman et al. 1996, Koster and Lynch 1991, Sauter et al. 1996). Instead, key compounds such as sucrose, raffinose, and stachyose are more greatly affiliated with the cold acclimation process (Ashworth et al. 1993, Berrocal-Lobo et al. 2011, Fennell 2004, Gusta et al. 2005, Hamman et al. 1996, Koster and Lynch 1991, Nagao et al. 2006, Sauter et al. 1996). In regards to grapevine buds, sugars are greater in basal buds than intermediate or apical buds; these buds are also more hardy (Badulescu and Ernst 2006, Edgerton and Shaulis 1953, Fennell 2004, Howell et al. 1978).

As with sugars, fatty acids (and fatty acid proteins) increase in concentration in cold hardy plants during the winter months as a result of starch degradation (Keller 2010, Lavee and May 1997, Xin and Browse 2000). Their importance in winter hardiness is centred upon their ability to stabilize and protect cell membranes. As such, during this time, lipids within cell membranes increase substantially, altering the membrane's structure (Fitter and Hay 2002, Sauter et al. 1996, Xin and Browse 2000). Unsaturated fatty acids are accumulated in favour of saturated fatty acids since they have a lower freezing point (Fitter and Hay 2002, Purves et al. 2003).

Cryoprotectants, such as the sugars and lipids previously described, protect plant cells by two major mechanisms: they either help cells tolerate extracellular ice or they allow the cells to supercool (Jones et al. 2000, Zabadal et al. 2007). To tolerate extracellular ice build up in vine tissues, cryoprotective compounds must prevent water loss within the cells. They do this by increasing solute concentrations within the cytoplasm (Koster and Lynch 1991, Xin and Browse 2000). This in turn lowers the osmotic potential of the cells, preventing water from exiting them (Xin and Browse 2000). Additionally, they can bind to and strengthen cell membranes by reducing their hydrated state (Zabadal et al. 2007). This protects the membrane from the physical stress of extracellular ice (Bohn et al. 2007, Keller 2010, Nagao et al. 2006, Sauter et al. 1996, Xin and Browse 2000).

Supercooling, on the other hand, inhibits the formation of ice by removing nucleation sites, thus preventing water molecules from binding together (Burke et al. 1976, Fitter and Hay 2002, Keller 2010, Wolfe and Bryant 1999). This process lowers the freezing point depression of water-based solutions by 1.86 ^{o}C for each mol of solute (Keller 2010). Sometimes, instead of crystallization, supercooling facilitates vitrification (glass formation) - a non-lethal liquid state within the cell (Nagao et al. 2006, Wolfe and Bryant 1999, Xin and Browse 2000). Using this mechanism, some deciduous plants can supercool to temperatures below -40 ^{o}C (Burke et al. 1976). Grapevine buds also supercool (Fennell 2004, Jones et al. 2000, Zabadal et al. 2007). Buds also create an impermeable organic barrier between them and the ice-filled cane that is very effective at preventing ice crystals or nucleation molecules from entering the bud site (Fennell 2004, Jones et al. 2000, Keller 2010).

1.1.3 Deacclimation, reacclimation, and breaking dormancy

Winter dormancy and cold acclimation are effective for the same amount of time – beginning in earnest in late fall and continuing until early spring (Lambers et al. 2008, Sauter et al. 1996). Many vines are able to withstand temperature fluctuations with the onset of spring and can undergo reacclimation, a process by which buds and other important tissues can re-enter a state of dormancy, supercooling, and water restriction (Fennell 2004, Keller 2010). Considerable loss in hardiness can occur during these fluctuations but most of this can be restored with a return to sub-zero temperatures (Fennell 2004, Kalberer et al. 2006, Keller 2010, Sauter et al. 1996). It is interesting to note, however, that those cultivars with the greatest winter hardiness are not always the ones with the greatest ability to reacclimate (Kalberer et al. 2006, Zabadal et al. 2007). For example, Wolf and Cook (1992) found that Concord, while displaying the greatest winter hardiness, deacclimated faster than the less hardy Cabernet Sauvignon.

With continuously warm weather, the ability of vines to reacclimate becomes impossible, at which point dormancy is broken (Hamman et al. 1990, Kalberer et al. 2006, Lavee and May 1997). Sugar concentrations decrease, starch concentrations increase, and water moves up from the roots to replenish the areas of the vine that have been suffering from dehydration (Hamman et al. 1996, Keller 2010, Sauter et al. 1996). Eventually, the buds break open and a new growing season has begun.

1.2 The importance of *terroir*, water metrics, and their relationship to winter hardiness

1.2.1 Characteristics of cool climate wine regions and the concept of *terroir*

In the world of grapes and wine many cool climate regions exist. The term cool climate is somewhat misleading. It does not refer to an overall temperature but instead refers to the cool conditions preceding grape harvest (van Leeuwen and Seguin 2006). In general, most cool climate viticultural areas in Europe and North America begin to harvest their grapes as soon as temperatures start to decrease (van Leeuwen and Seguin 2006). As such, grape cultivars grown in these regions must be able to achieve full ripeness during the fall, before the onset of winter. For *Vitis vinifera* cultivars, this can occur over a lengthy span of two months – from September to November in the Northern hemisphere (van Leeuwen and Seguin 2006). But temperature and climate are not the only factors affecting the growth of grapes and the quality of their resulting wines. In fact, cool climate wine regions can be excellent examples of *terroir* expression.

Terroir, a French term, is well expressed in cool climate wine regions (van Leeuwen and Seguin 2006, Seguin 1986). It does not seem to have any concrete definition, leading to some authors to call it a mystical term (Douglas et al. 2001, Jackson 2009, Vaudour 2002). However, the reason for this lack of definition stems from the evolution of the term itself. In simplest terms the *terroir* effect describes the ability for a wine to express its origins through sensory characteristics. Seguin (1986) postulates that *terroir* is mostly a geological and pedology (soil-based) characteristic whereby geological formations and soil type dictate the quality of grapes and wine. This definition can be expanded to include all geographical influences including human geography which can affect the establishment and growth of wine regions (van Leeuwen 2010, van Leeuwen and Seguin 2006, Vaudour 2002). Therefore, viticultural practices and oenological techniques can also affect *terroir* (van Leeuwen 2010, van Leeuwen and Seguin 2006). Relying on physical and human geography alone can fail, however. For instance, due to climate conditions, vineyards once located close to Paris were unable to achieve ripeness and were removed (van Leeuwen and Seguin 2006).

Once again the definition of *terroir* has to be broadened; climate must come back into the picture. *Terroir* is then viewed as the interaction between the vines and their environment as a whole, including topographical, pedological, climatic, and human-based factors (Douglas et al. 2001, Koundouras et al. 2006, van Leeuwen 2010, van Leeuwen and Seguin 2006, Vaudour 2002, Wine Council of Ontario 2011). Climatic characteristics of particular importance include precipitation, temperature, and the length of the growing season, all of which can affect berry composition and quality (Gillerman et al. 2006, van Leeuwen 2010). The effect of these factors can be controlled somewhat by proper vineyard selection and management (i.e., controlling cultivar selection, trellising height, and vine size): this has become the subject of *terroir*-based scientific research and thus has led to a scientific definition of the concept (Vaudour 2002).

The scientific definition of *terroir* is founded upon the basic concept that vineyard location affects the vines and thus their fruit (Reynolds et al. 2007, Schlosser et al. 2005).

It encompasses environmental characteristics - physicochemical properties of the soil, the topography of the land, and mesoclimate (regional climate) – as well as vine biology – cultivar, rootstock, age, and metabolism (Reynolds et al. 2007, van Leeuwen 2010, van Leeuwen and Seguin 2006). Research into the interactions between grapevines and their environment has led to key discoveries that support the notion of *terroir* even for New World wine regions. For instance, Bramley and Hamilton (2004) and Bramley et al. (2011) found that vineyards in Australia had temporally stable patterns of vine attributes such as trunk circumference, soil conductivity, and yield. These patterns were related to the characteristics of the growing region (Bramley and Hamilton 2004, Bramley et al. 2011). Additionally, in another study, Gillerman et al. (2006) were able to describe the *terroir* of the Western Snake River Plain in Idaho, USA using its geological history, soil type, and climate. By using this information, they were able to support the decision to grow cold hardy white cultivars in the area. These cultivars, including Riesling, Chardonnay, and Gewurztraminer, have been planted in the region to take advantage of the river, the sloping terrain, and the good air drainage resulting from this topography (Gillerman et al. 2006).

1.2.2 *Terroir* of the Niagara Peninsula

Located in the province of Ontario, Canada, the Niagara Peninsula is another appellation that has benefitted from research on the concept of *terroir*. As with many other wine regions around the world, it is located between the 30^o and 50^o Northern latitudes (more specifically 41^o and 44^o; van Leeuwen and Seguin 2006, Wine Council of Ontario 2011). This cool climate region benefits from the close proximity of Lake Ontario, an ancient seabed rich in limestone, an escarpment with sloping hillsides, and a heterogeneous soil structure due to prehistoric glacial activity – all of which can aid in the production of unique, world class wines (Reynolds et al. 2007, Schlosser et al. 2005, Shaw 2005, van Leeuwen and Seguin 2006, Wine Council of Ontario 2011). Niagara's intricate *terroir* first led to the differentiation of three sub-appellations: Lakeshore, Lakeshore Plains, and the Escarpment Bench (Douglas et al. 2001, Hakimi Rezaei and Reynolds 2010, Schlosser et al. 2005, Wine Council of Ontario 2011). Since then, the VQA (Vintner's Quality Alliance) of Ontario has designated two regional appellations (Niagara-on-the-lake and Niagara Escarpment) and ten sub-appellations (Wine Council of Ontario 2011). These include: Creek Shores, Lincoln Lakeshore, Vinemount Ridge, Beamsville Bench, Short Hills Bench, Twenty Mile Bench, Four Mile Creek, Niagara Lakeshore, Niagara River, and St. David's Bench (Fig. 1.1; Hakimi Rezaei and Reynolds 2010, Wine Council of Ontario 2011).

The Niagara Peninsula appellation receives approximately 1400 growing degree days (GDDs, number of degrees above a baseline of 10 ^{o}C) which allows the region to grow 6100 ha of mostly cold hardy *Vitis vinifera* cultivars, such as Riesling, Gewurztraminer, Pinot noir, and Cabernet franc (Clore et al. 1974, Shaw 2005, van Leeuwen and Seguin 2006, Wine Council of Ontario 2011). Other cultivars are also grown but less cold hardy cultivars must be planted in areas which receive enough sun exposure and GDDs, such as in the Lakeshore Plains (Hakimi Rezaei and Reynolds 2010, Schlosser et al. 2005). In comparison, Escarpment Bench receives good air movement and drainage but less sunlight and cooler temperatures, while the Lakeshore's climate is moderated by the lake, with warmer winters but cooler summers (Hakimi Rezaei and Reynolds 2010, Schlosser et al. 2005, Shaw 2005). As the slopes of the escarpment face north (not south, which is ideal), the ability of the vines to receive ample sunlight during the growing season is of great concern (Schlosser et al. 2005, Shaw 2005). Along with sun exposure, water availability (and use) by the vines is also important and has become a main focus in *terroir* studies not just in Canada but in wine regions around the world.

1.2.3 The importance of water metrics

Of all the factors affecting plant growth and development, water availability is by far the most important. Water is not only used by the plant to produce carbohydrates (energy) but also to provide structural support, cooling, and transportation of macro- and micronutrients (Purves et al. 2003). Plants obtain water (and nutrients) from the soil. As such, soil type and water content are influential to the vegetative expression of all plants, including grapevines (Acevedo-Opazo et al. 2008, Koundouras et al. 2006, Purves et al. 2003). Soil water content is often measured as soil moisture percentage and has been found to be strongly correlated with water use and growth of grapevines (Mullins et al. 1996, Sivilotti et al. 2005, van Leeuwen and Seguin 2006, Williams and Araujo 2002).

Water moves from the soil into plant roots by osmosis. It is transported to the leaves in the xylem tissue by means of a transpiration-cohesion-tension mechanism (Purves et al. 2003). This mechanism is controlled by mesophyll cells, which undergo photosynthesis, and specialized plant cells, known as guard cells (Purves et al. 2003). These cells control the opening and closing of stomata – openings within the leaf that facilitate the diffusion of carbon dioxide and evapotranspiration of water (Purves et al. 2003). As the plant loses water through the stomata, a water potential (ψ) gradient is created (Kennedy et al. 2002, Koundouras et al. 2006, Matthews et al. 1987, Reynolds et al. 2010a, Williams and Araujo 2002). This ψ increases tension within the leaf apoplast which then draws in water from the xylem tissue (Purves et al. 2003). Water molecules which adhere together by hydrogen bonding (cohesion) then move through the vascular tissue to replenish the water supply (Purves et al. 2003). Upon limited water supply and non-ideal temperatures (> 35 ^{o}C), leaf stomata close, photosynthesis is reduced, and the vine can experience water stress (Mullins et al. 1996, Purves et al. 2003).

The extent to which a vine uses water is known as its vine water status and is influenced by climate, soil, and vine management (in other words, components of *terroir*; Taylor et al. 2010, van Leeuwen and Seguin 2006). Vine water status is numerically represented by the ψ of the vine which is measured primarily in megapascals (MPa) or bars, where one bar is equivalent to 0.1 MPa. A grapevine's ψ decreases from root to apical tip and is the sum of the solute and pressure potentials (Purves et al. 2003). Leaf ψ is the most commonly reported value and is measured using the pressure bomb technique developed by Scholander et al. (1965) and elaborated upon by Turner (1988). This method, which uses a pressure chamber to force xylem sap from the petioles of leaves (Basinger and Hellman 2006, Purves et al. 2003, Scholander et al. 1965, Turner 1988, Williams and Araujo 2002), can indicate water stress in grapevines. For instance, Ojeda et al. (2002) stated that water deficits were experienced once leaf ψ values dropped below -10 bars. Leaf ψ values are also indicative of irrigation practices. Kennedy et al. (2002) reported that heavily irrigated vines displayed average leaf ψ of approximately -11 bars to -8 bars, standard irrigation practices produced leaf ψ of -13 bars to -10 bars, and deficit irrigation vines had leaf ψ of -17 bars to -14 bars. Similar results were reported by

Williams and Araujo (2002), with high leaf ψ (low water stress) values of -7.0 bars and low leaf ψ (high water stress) values of -18 bars.

Grapevines are one of the few woody plants that perform well in water stressed conditions, most often producing quality wines because of it (Koundouras et al. 2006, van Leeuwen and Seguin 2006). Under natural conditions, the leaf ψ of vines can vary spatially within a vineyard since root depth, soil water retention, evapotranspiration rates, and sun exposure can all affect water status (Koundouras et al. 2006, Taylor et al. 2010). Additionally, the more soil water available to the vines (also dictated by root depth), the more vigorous their growth will be. When copious amounts of water are available to the vines, they can sometimes suffer from self-induced water stress (and low leaf ψ) due to high energy demands (Acevedo-Opazo et al. 2008, Keller and Mills 2007). Vines can suffer from water stress due to the lack of available water as well. For instance, Koundouras et al. (2006) found that vines planted on shallow silt/loam soil with limestone bedrock had limited root growth and water access and therefore displayed low vine size and highly negative leaf ψ as well. These natural water deficits can increase water stress within vines. However, research has shown that berry composition and wine quality can benefit from this. Water stress can inhibit vine growth, producing smaller berries that have higher concentrations of soluble solids, anthocyanins and phenols (red cultivars), and lower titratable acidities (Koundouras et al. 2006, Matthews and Nuzzo 2007, van Leeuwen and Seguin 2006). In addition, they can accelerate the ripening of berries, lower yields, and increase wine aromas and flavours (Koundouras et al. 2006, van Leeuwen and Seguin 2006).

Knowledge of the relationship between soil moisture, leaf ψ, and berry quality has led to countless experiments on the implementation of deficit irrigation (Acevedo-Opazo et al. 2010, Basinger and Hellman 2006, Ojeda et al. 2002, Roby et al. 2004, Sivilotti et al. 2005, Shellie 2010). Deficit irrigation is defined as a restriction of water application to a farm or vineyard in order to conserve water, reduce vegetative growth, and optimize fruit quality (Basinger and Hellman 2006, Gillerman et al. 2006). Regulated deficit irrigation strategies maintain low soil moisture and moderate water stress on the vines between fruit set and véraison (Basinger and Hellman 2006). Although deficit irrigation methods can change the *terroir* of a vineyard (van Leeuwen and Seguin 2006), the vine effects of natural water stress conditions also occur in deficit irrigation trials (Ojeda et al. 2002, Roby et al. 2004, Shellie 2010). The exception is a study by Basinger and Hellman (2006) who found that regulated deficit irrigation had no effect on yield, berry weight, soluble sugars, or titratable acidity in a vineyard in Texas. However, these non-significant results may have been due to the extremely dry conditions in the region during the study period, leading to water stress even in control plots (Basinger and Hellman 2006).

Deficit irrigation is not the only type of irrigation practiced. In many cases measurements of leaf ψ are also used to ensure that vines are sufficiently irrigated to avoid detrimental water stress (Gillerman et al. 2006, Williams and Araujo 2002). In such cases, irrigation can be applied at phenologically important stages using drip lines (Gillerman et al. 2006). Over-intensive irrigation can have the opposite effect of deficit irrigation, contributing to high vine size, yields, and berry weights and thus lower quality wines (Seguin 1986). Therefore, as with winter hardiness, great care must be taken to manage the water status of vines in such a way as to maximize the natural *terroir* of the region.

1.2.4 Winter hardiness and its relationships to other *terroir* characteristics

Water metrics are not the only characteristics which bridge environmental, biological, and human aspects of *terroir* – winter (bud) hardiness does also. As with other vine characteristics, bud hardiness is affected by the location and environmental conditions of a vineyard. Especially in areas with low winter temperatures, freeze injury is of major concern as bud survival is highly correlated with atmospheric temperature (Wolf and Cook 1992). Therefore, cultivars must be carefully chosen to fit the regional climate in which they are to be grown (Campoy et al. 2011, Clore et al. 1974, Fennell 2004, Gillerman et al. 2006, Jones et al. 2000, Lisek 2007, Zabadal et al. 2007). Particular attention must be paid also to air flow and drainage within a region (Gillerman et al. 2006, Zabadal et al. 2007). For instance, although the Niagara Peninsula reaches low temperatures during the winter months, Lake Ontario and the slopes of the escarpment provide sufficient air circulation to prevent pooling of cold air along the Bench and the Lakeshore (Shaw 2005). However, pooling of cold air can still occur in the Lakeshore Plain region (Shaw 2005). Sun exposure is also of particular importance since it has been found that hardiness levels in well-exposed vines are higher than those in shaded conditions (Fennell 2004, Howell and Shaulis 1980, Zabadal et al. 2007). In particular, Howell and Shaulis (1980) reported that Concord bud hardiness was highest in canes that had been well exposed to direct sunlight during the previous growing season. Therefore the location of a vineyard is a significant factor controlling the survival of overwintering buds.

Water availability and use by the plant also affects bud hardiness. As previously mentioned, when experiencing water stress vines tend to produce what is seen as higher quality fruit. This same phenomenon is observed in regards to winter hardiness where vines with lower water status and soil moisture enter dormancy and acclimate earlier. For instance, Koundouras et al. (2006) found that growth cessation of Agiorgitiko grapevines in Greece was highly correlated with both earliness and intensity of vine water stress. This result was supported by Basinger and Hellman (2006) who noted that Cabernet Sauvignon grapes subjected to moderate water deficits developed periderm faster (58% by July 24) than non-deficit irrigated vines (33% by July 24). In addition, Keller (2005) noted that low soil moisture was related to higher ABA levels. It is interesting to note, however, that vine water deficits and earlier shoot acclimation did not correspond to increased winter hardiness (Basinger and Hellman 2006). Regardless, it is recommended that vines be exposed to water stress towards the end of the growing season in order to promote acclimation (Gillerman et al. 2006, Keller 2005).

As previously discussed, the more water available to a vine, the greater the vegetative growth. If water deficits are detrimental to vine growth but advantageous for cold acclimation, then reduced vine size must also promote cold hardiness. High-vigour vines mature more slowly and being more prone to winter injury (Clore et al. 1974, Howell et al. 1978, Zabadal et al. 2007).When investigating within-vine variations in bud cold hardiness of Riesling and Vignoles vines in NY State, Howell and Shaulis (1980) found that canes with lateral growth had much lower survival compared to canes with no laterals. Vine size is not just affected by water status but also by macronutrients such as nitrogen. Nitrogen is considered one of the main factors affecting not only vine size but also yield and fruit quality (van Leeuwen 2010, van Leeuwen and Seguin 2006, Zabadal et al. 2007). Although beneficial to the plant during the growing season, at harvest higher nitrogen levels increase vegetative growth and water demands, and decrease cold tolerance (Scagel et al. 2010, van Leeuwen 2010). Additionally, plants with access to less nitrogen developed earlier and deeper cold tolerance than their vigorous counterparts (Scagel et al. 2010). High-yielding vines are also more prone to winter injury, possibly also because of delayed cold acclimation and dormancy, while low yielding vines have greater freeze tolerance (Fennell 2004, Howell et al. 1978, Lisek 2007, Zabadal et al. 2007). However, time of harvest (normal compared to delayed) has not been found to effect bud hardiness (Hamman et al. 1996).

After harvest, once the vines have entered a state of dormancy vineyard managers often begin pruning. Research on the effect of pruning on grapevine winter hardiness has thus far been inconclusive. Studies have found that the tips of fall-pruned canes had considerably more cane and bud damage than unpruned canes (Edgerton and Shaulis 1953, Wolpert and Howell 1984). However, Wolpert and Howell (1984) reported that, in general, fall-pruned vines were hardier. It was also found that dormant vines pruned earlier in the winter were considerably less winter hardy that vines pruned later, by at least 1.5 ^{o}C. In contrast to either study, Howell et al. (1991) reported that more severely pruned vines had greater bud survival and Hamman et al. (1990) found no significant influence of pruning on bud hardiness or survival at all. Regardless of the effects of pruning on winter hardiness, it is still beneficial to prune close to winter's end to select healthy canes free of damage and to control yield (Howell et al. 1978, Keller and Mills 2007, Wolpert and Howell 1984).

Research on the interactions between vineyard characteristics and bud hardiness is extremely important, especially in areas where cold injury is a concern. Using this research, beneficial management decisions can be made to ensure the survival of vines during the winter months. These include planting vines to a sufficient root depth, training vines to multiple trunks (in case of trunk freeze injury), optimizing canopy management for proper sun exposure and balance, and reducing crop load (Fennell 2004, Gillerman et al. 2006, Howell and Shaulis 1980, Shaw 2005, van Leeuwen and Seguin 2006). However, many of the relationships between bud hardiness and *terroir* have not been satisfactorily studied, especially in regards to water metrics (so far focussing on dormancy induction; Basinger and Hellman 2006, Gillerman et al. 2006, Koundouras et al. 2006) and berry composition (no studies thus far).

1.3 Scientific developments in the *terroir* of winter hardiness: measuring bud hardiness and the use of geographic information systems

1.3.1 Measuring bud hardiness

Although there has been insufficient work done regarding bud hardiness and the *terroir* of grapevines, ample research has been done regarding bud hardiness measurements. Generally speaking, there are two ways of measuring bud hardiness. The first, and most simple, is to measure bud survival. The second, more complicated method is to measure bud LT_{50} values – the temperature at which 50 % of primary buds die by artificial freezing (Zabadal et al. 2007).

Bud survival/mortality methods have been in use for decades. Edgerton and Shaulis (1953) were among the first to evaluate bud survival from the browning of bud tissue. Known as the browning test by some authors, the method involves shaving the fruiting buds of canes using a razor until the primary bud tissue has been exposed (Howell et al. 1978, Wolf and Cook 1994). In general, cane samples are collected and acclimatized to room temperature for 24 to 72 hours before bud shaving and exposure (Fennell 2004, Mills et al. 2006, Wolf and Cook 1994, Zabadal et al. 2007). However, some studies report allowing the buds to thaw for up to seven days (Fennell 2004, Hamman et al. 1996). If upon sampling the primary bud is green in colour then it is alive (Fennell 2004, Zabadal et al. 2007); if the bud is brown in colour then it is dead, as this is a sign of oxidative and freeze damage (Fennell 2004, Hamman et al. 1996, Lisek 2007, Mills et al. 2006, Zabadal et al. 2007). Although an informative test, bud survival assessments are usually paired with laboratory freezing tests in order to strengthen the results of bud hardiness studies (Clore et al. 1974, Edgerton and Shaulis 1953, Fennell 2004, Hamman et al. 1996, Howell et al. 1978, Howell and Shaulis 1980, Mills et al. 2006, Wolf and Cook 1994, Wolpert and Howell 1984). These two methods are often in agreement with one another when tested on the same cane tissues, lending credibility to both methods (Mills et al. 2006, Wolf and Cook 1994).

Bud hardiness trials have taken on many forms over time. Some are quite elaborate and expensive methods, such as using nuclear magnetic resonance (NMR) spectroscopy to quantitatively define the amount of water freezing within plant material (Burke et al. 1976). Other methods are much easier to apply. For instance, Howell et al. (1978) wrapped test samples in aluminum foil, placed them in insulated flasks and subjected them to a 5 ^{o}C per hour temperature decrease within a programmable freezer. The buds were then assessed for survival by the browning method (Howell et al. 1978). Wolpert and Howell (1984) and Schnabel and Wample (1987) used similar procedures by removing samples during different temperature points to determine a T_{50} value (temperature at which 50% of the buds were brown). A 3 ^{o}C per hour temperature drop from 0 to -24 ^{o}C was used in the latter example. A similar method was executed by Hubácková et al. (1996) except buds were not assessed for survival by shaving but were instead placed in boxes with water at room temperature to promote bud burst. Edgerton and Shaulis (1953) used a particularly interesting method accompanied by bud survival assessments. In their study, samples were exposed to low temperatures (2 to 3 ^{o}C decrease per hour to -27 ^{o}C) within an antifreeze solution (Edgerton and Shaulis 1953). The samples were then tested for electrical conductance where more severely injured tissue would release a greater amount of electrolytes due to membrane rupturing (Edgerton and Shaulis 1953, Fennell 2004). Although effective, these methods are not the most widely used in current research.

The two most popular procedures for measuring bud hardiness are thermal analysis and differential thermal analysis (DTA; Burke et al. 1976). First developed with the emergence of programmable freezers (Clore et al. 1974, Howell and Shaulis 1980), these two methods are extensively used in grapevine bud studies (Badulescu and Ernst 2006, Basinger and Hellman 2006, Hamman et al. 1990, Hamman et al. 1996, Mills et al. 2006, Wolf and Cook 1994). Both are calorimetric methods which measure exothermic releases of heat upon the freezing of intracellular, supercooled water molecules within plant tissue (Burke et al. 1976, Fennell 2004, Wolf and Cook, 1994). Both also record the presence of high temperature exotherms (HTE, cause by extracellular ice) and low temperature exotherms (LTE, caused by intracellular ice; Badulescu and Ernst 2006, Fennell 2004, Zabadal et al. 2007). The main difference between the two is that differential thermal analysis makes use of an external reference cell to record the temperature at which a bud dies and plots this information graphically to determine the LT_{50} of the sample (Burke et al. 1976).

In essence, both methods involve excising buds from the cane tissue, keeping the barrier between the bud and the cane intact (Basinger and Hellman 2006, Fennell 2004, Mills et al. 2006). The samples are then set into a programmable freezer that drops temperatures at approximately 3 to 4 ^{o}C per hour until a set minimum temperature is achieved (Basinger and Hellman 2006, Mills et al. 2006, Wolf and Cook 1992). Variations of this method use either aluminum or Parafilm wrapping (Hamman et al. 1996, Wolf and Cook 1992), or ceramic plating to house the samples and conduct exothermic energy that is then recorded by thermocouples (Basinger and Hellman 2006, Fennell 2004, Hamman et al. 1990, Mills et al. 2006, Wolf and Cook 1994). In most cases moistened filter paper is used to improve the conduction of exothermic energy (Fennell 2004). Modifications of freezer methods continue to be made. For instance, Mills et al. (2006) equilibrated their DTA bud samples for an hour at 4 ^{o}C to allow the samples to reach an equal temperature. In addition, multiple sample trays were also added to increase sample throughput, and air circulation throughout the freezer was improved (Mills et al. 2006). Other changes have also been made which have been adopted for this present research project including reporting the bud LT_{50} value as the median LTE, as introduced by Wolf and Cook (1992, 1994). Regardless of the TA or DTA method used, the results of these methods show that grapevine buds die between -11 ^{o}C to -24 ^{o}C in cool climate regions, a result which once again agrees with bud survival (browning) trials (Badulescu and Ernst 2006, Mills et al. 2006, Wolf and Cook 1994).

1.3.2 Precision viticulture and geographic information systems

In order to understand the *terroir* of bud hardiness it is necessary to delve deeper into the spatial relationships between it and other factors. Precision viticulture, which is related to the concept of *terroir*, can help achieve this by using techniques involving GIS. It is defined as a crop management technique which recognises that a plot of land does not have homogenous characteristics, allowing for the spatial investigation of factors within a production area (Bramley 2005, Bramley and Hamilton 2004). Precision viticulture is used to delineate management zones – sub-regions which display uniform environmental conditions - within vineyards in order to produce fruit which displays the positive attributes of a *terroir* (Bramley 2005, Bramley and Hamilton 2004, Bramley et al. 2011, Morari et al. 2009). The process of precision viticulture first begins within the vineyard where observations are made, followed by analysis, evaluation, and implementation of more spatially targeted management strategies (Bramley and Hamilton 2004). Using this technique, more informed decisions can be made when applying segmented harvest, irrigation, pruning, vine maintenance, and fertilization plans (Bramley and Hamilton 2004, Reynolds et al. 2007). Research involving precision viticulture has been used to identify temporally stable spatial patterns of yield components, supporting the notion that zonal management strategies are effective in vineyards (Bramley and Hamilton 2004, Bramley et al. 2011).

One of the most important tools utilized by precision viticulture techniques, GIS, is now being applied to *terroir* studies (Bramley and Hamilton 2004). Defined as computer-based systems specializing in assembling, modifying, and presenting geographic information, GIS techniques can accurately represent GPS data and depict images with high spatial resolution (Morari et al. 2009, Vaudour 2002). Some analyses can also be completed with the same software, adding to the versatility of this technique. The use of GIS in *terroir* research has only recently come to the forefront. Gillerman et al. (2006) referred to the use of GIS when studying the heterogeneous soil composition of vineyards in Idaho, USA; Reynolds et al. (2007) used GIS methods to define the spatial variability and *terroir* within a Riesling vineyard in Ontario, Canada; and Acevedo-Opazo et al. (2008) utilized GIS technology to define the spatial variability of water status in a vineyard in the Languedoc-Roussillon region of France.

One of the most important GIS procedures used in viticultural research is spatial interpolation. Spatial interpolation predicts the values of properties at unsampled locations based on known observations throughout the mapping field (Bramley 2005, Erdogan 2009). Most interpolation methods make use of Tobler's First Law which states that points closer in proximity to each other are more similar than points further away (Miller 2004). There are two main categories of interpolation methods: deterministic interpolation (such as inverse distance weighting, IDW) and geostatistical interpolation methods (such as kriging; Erdogan 2009). IDW is used by various studies (Acevedo-Opazo et al. 2008, Reynolds et al. 2007) and is a simple, linearly-weighted algorithm based on an inverse distance function (Erdogan 2009). Although effective, IDW relies heavily on Tobler's First Law and does not report errors associated within interpolation models (Bramley and Hamilton 2004).

In contrast, kriging relies more heavily on pre-existing trends within the data and provides error or uncertainty predictions to indicate the quality of the interpolations made (Bramley and Hamilton 2004, Erdogan 2009). As such, it is more heavily used in scientific studies (Bramley 2005, Bramley and Hamilton 2004, Bramley et al. 2011, Erdogan 2009). Kriging comes in many forms; the most frequently used are ordinary and simple kriging which differ only in their assumption of spatial means (Erdogan 2009). Regardless of the type of kriging used, the interpolation relies upon the use of a semi-variogram (Bramley 2005, Lyon et al. 2010). Semi-variograms define the spatial dependency and the contribution of each known data point in order to produce an accurate interpolation (Ahmadi and Sedghamiz 2008, Bramley 2005, Erdogan 2009).

Spatial interpolations are extremely powerful tools for viticultural studies. These methods are even stronger when paired with other methods of data evaluation, such as multivariate statistics. These include the use of principal components analysis, data-clustering techniques, and correlation tables (Acevedo-Opazo et al. 2008, Acevedo-Opazo et al. 2010, Bramley et al. 2011, Bramley and Hamilton 2004, Morari et al. 2009, Reynolds et al. 2007). Principal component analysis is effective since it allows for the analysis of a whole data set, investigating multiple interactions among variables (Acevedo-Opazo et al. 2008, Morari et al. 2009). Data-clustering techniques group similar sample points together, further displaying variations and patterns within the data (Bramley 2005, Bramley et al. 2011, Morari et al. 2009). When used in tandem with GIS, these procedures can greatly increase the amount of information derived from vineyard measurements. As a result of their effectiveness and versatility, GIS techniques are of great importance not only to *terroir* studies but to geographic studies in general. In regards to the spatial analysis of bud hardiness, the robustness of the methods described can only increase the potential information uncovered.

1.4 Conclusions

It is abundantly clear that much is known about winter injury, cold acclimation, water status, and the concept of *terroir*. In addition, a great many cultural practices are already known to enhance the survival of grapevine buds in regions where cold winters are common. However, the spatial relationships and variability of winter hardiness, especially in uncontrolled studies, is not known. Of greater concern is the lack of relationships established between winter hardiness and many other important *terroir* factors such as water status, yield, and fruit composition. The evolution of DTA and GIS methods may finally allow for these investigations to be undertaken. By utilizing the advancements made in spatial analysis studies, it will be possible to assess the spatial relationships among these variables.

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Chapter 2: The Importance of Water Metrics and Yield Measurements – Relationships with Vineyard Characteristics in the Niagara Region

2.1 Introduction

Water is used by grapevines to produce energy, provide structural support, allow for cooling, and to transport solutes throughout the plant structure (Purves et al. 2003). Water use by grapevines is quantitatively expressed by its leaf water potential (ψ), which decreases from root to leaf (Purves et al. 2003). Often, leaf ψ is measured using the pressure bomb technique which can be applied prior to dawn (predawn leaf ψ) or at midday (midday leaf ψ; Williams and Araujo 2002). Regardless of which method is used, leaf ψ is accepted as an accurate way to measure water use by the vine (Koundouras et al. 2006, Williams and Araujo 2002). Leaf water potential values were found by Taylor et al. (2010) to be primarily influenced by cultivar early in the growing season and by soil type during the hotter months of the summer. Soil is an important factor controlling the vegetative expression of grapevines as it affects a vine's access to water and nutrients (Acevedo-Opazo et al. 2008, Keller 2005, Koundouras et al. 2006, Purves et al. 2003). Of great importance, soil water content is often measured as soil moisture percentage and has been found to be strongly correlated with ψ and vine size (Mullins et al. 1996, Sivilotti et al. 2005, Sweet and Schreiner 2010, van Leeuwen and Seguin, 2006, Williams and Araujo 2002). For instance, Koundouras et al. (2006) found that vines with reduced soil water availability displayed low vegetative growth and accelerated growth cessation. This is often a result of shallow root systems which restrict the amount of water available to the vine (Koundouras et al. 2006). In addition, a decrease in soil moisture (and thus nutrient availability) reduces rates of photosynthesis, thus affecting leaf ψ values (Keller 2005, Sivilotti et al. 2005). Soil water availability has also been shown to have effects on berry composition. Sivilotti et al. (2005) found that decreased soil moisture was related to lower berry weight and increased anthocyanin concentrations. No results were found regarding Brix, TA, or pH. In contrast, Acevedo-Opazo (2010) reported that restricted soil moisture led to greater anthocyanin concentrations but also increases in soluble solids in Cabernet Sauvignon.

The soil moisture and water status of a vineyard can have significant effects on vigour, yield, and berry composition. In separate studies on Merlot and Agiorgitiko grapes, an increased water deficit (measured by midday leaf ψ) led to lower titratable acidity, inhibited vegetative growth, and limited berry size (Koundouras et al. 2006, Shellie 2010). Additionally, for Agiorgitiko, Cabernet Sauvignon, and Shiraz, smaller berries had higher concentrations of anthocyanins, phenols, and sugar as a result of water stress (Kennedy et al. 2002, Koundouras et al. 2006, Ojeda et al. 2002, Roby et al. 2004). In white grape varieties, decreases in ψ have been associated with increased soluble solids (Reynolds et al. 2010a; Reynolds et al. 2010b). Additionally, Riesling monoterpenes increase in concentration with significant water deficits and smaller berry size (Reynolds et al. 2010a, Reynolds et al. 2010b).

In addition to affecting concentrations of soluble solids, soil moisture and water status can also affect the ripening of berries, change wine aromas and flavours, and affect yields (Koundouras et al. 2006, van Leeuwen and Seguin 2006). Often, more negative leaf ψ is associated with low yields and higher berry quality, while high leaf ψ promotes high yields and lower berry quality (Mazza et al. 1999, Roby et al. 2004, van Leeuwen and Seguin 2006). Yield itself has been spatially related to other berry composition variables such as Brix, pH, and TA (Bramley 2005). It is postulated that high water uptake causes an increase in yield before it increases positive berry characteristics, diluting many solutes (van Leeuwen and Seguin 2006). However, if the soil and vines can support higher yields, berries with high concentrations of solutes can still be grown (van Leeuwen and Seguin 2006).

Research has shown that leaf ψ and yield of vines can vary spatially between and within vineyards, with factors such as slope, evapotranspiration rates, sun exposure, climate, and the aforementioned root depth and soil water availability strongly affecting it (Bramley and Hamilton 2004, Koundouras et al. 2006, Taylor et al. 2010). As such, water availability and use are important factors affecting the *terroir* of a vineyard. The concept of *terroir* is defined as the interaction between the environmental, biological, and oenological characteristics of a vineyard (Reynolds et al. 2007, van Leeuwen and Seguin 2006). *Terroir* is therefore unique to each individual vineyard, as well as the region in which it is located. *Terroir* research now frequently employs the use of GIS. One of the most important GIS procedures used in viticultural research is spatial interpolation which predicts the values of properties at unsampled locations, allowing for the spatial distribution of a variable to be mapped and visualized (Bramley 2005, Erdogan 2009).

Although many relationships have been elucidated between water metrics, berry composition, and vine characteristics around the world, little is known about the effect of water metrics on the *terroir* of Canadian wine regions. This study, therefore, is focussed on the spatial relationships of soil moisture and leaf ψ of Cabernet franc and Riesling vineyards located in the cool climate region of the Niagara Peninsula in Ontario, Canada. Past research in the region has differentiated between three areas (Lakeshore, Lakeshore Plains, and the Escarpment Bench), two regional appellations (Niagara-on-the-lake and Niagara Escarpment), and ten sub-appellations (Creek Shores, Lincoln Lakeshore, Vinemount Ridge, Beamsville Bench, Short Hills Bench, Twenty Mile Bench, Four Mile Creek, Niagara Lakeshore, Niagara River, and St. David's Bench; Douglas et al. 2001, Hakimi Rezaei and Reynolds 2010, Schlosser et al. 2005, Wine Council of Ontario 2011). With the use of GIS and spatial interpolations, spatial patterns of water metrics were expected to be found within the blocks studied. It was also hypothesized that varietal and block variations would be seen regarding the relationships between water metrics and other vineyard and berry characteristics. As with other studies, lower water status and soil moisture were expected to promote lower yields and berry weight, and higher concentrations of berry solutes.

2.2 Materials and Methods

2.2.1 <u>Site selection</u>

Six commercial vineyard blocks of both Riesling and Cabernet franc were chosen for this project. Efforts were made to investigate the Niagara region as a whole and, as such, the chosen blocks were located in five of the ten sub-appellations of the Niagara Peninsula, including: Niagara Lakeshore, Lincoln Lakeshore, Four Mile Creek, Beamsville Bench, and St. David's [Vintners' Quality Alliance (VQA) 2009]. The sites are referred to as follows: Buis, George, Hughes, Lambert, Cave Spring and Lowrey Riesling; Buis, George, Kocsis, Lambert, Cave Spring and Lowrey Cabernet franc. General features of each vineyard and their geographic location can be found in Table A1 and Figure A22. General canopy management included hedging and basal leaf removal for all blocks, and cluster thinning for Cabernet franc only.

Approximately 75 sentinel vines were chosen per block (single flagged vines), with a smaller subset of these vines for leaf ψ, bud LT_{50}, bud survival, and monoterpene analysis (15 to 24 vines). The vines selected as sentinel vines represented an ≈8 X 8 m grid (where possible), were healthy, and representative of the vines within the block. Characteristically, the blocks were rectangular in shape with a greater N/S range, with 29-195 sentinel vines/ha (95 vines/ha average) depending on the shape and extent of the vineyard. A Raven Invicta 115 GPS (Global Positioning System) Receiver, Raven Industries (Sioux Falls, SD) (with 1.0 to 1.4 m accuracy) was used to delineate the shape of each vineyard block and geolocate each sentinel vine. The coordinates from each block were imported into Excel sheets and visually represented using the GIS (geographic information system) program ArcGIS [Environmental Systems Research Institute (ESRI), Redlands, CA].

2.2.2 Water Metrics

i) Soil Water Status

Soil moisture data (% water by volume) was collected from each block on three separate dates between late June (fruit set) and early September (véraison) in the 2010 and 2011 growing seasons. Soil moisture was measured at each sentinel vine by time domain reflectometry using a Fieldscout TDR-300 soil moisture probe (Spectrum Technologies Inc., East Plainfield, IL). Measurements were made between ≈0900h and 1600h in order to reduce variability due to differing soil water evaporation rates as a function of temperature and humidity. Measurements were taken in the row ≈10 cm from the base of each vine trunk over a 20 cm depth (the length of the metal probes). As most vineyards in the region contain drain tiles at a 60 cm depth, which tends to restrict rooting depth, this depth was considered adequate for determining moisture levels. The mean soil moisture for each sentinel vine was calculated from two or three separate readings. Measurements were adjusted for high-clay soils. In all cases, efforts were made to ensure that the probes were completely inserted into the soil. Measurements were not recorded if the probes hit large amounts of rock material or air pockets. During the 2011 growing season, only two soil moisture measurements could be made due to equipment issues.

ii) Vine Water Status

Leaf ψ measurements were made concurrent with soil moisture measurements during the growing season using the double flagged vines only. There were three sampling dates for each block during the growing season in both 2010 and 2011. Leaf ψ measurements were made between 1100h and 1600h as this represents the time at which the vines were exposed to the highest intensity of sunlight. Two to three leaves were measured per vine. Chosen leaves were of average size, in full sunlight, and had no visible signs of damage or disease. Leaf ψ measurements were only made on cloudless days. In the event of rain, measurements were delayed for at least 24 hours.

Leaf ψ was measured using the pressure bomb technique (Turner 1988). The petiole of the chosen leaf was first cut with a sharp razor blade. The leaf was then inserted into a pressure chamber Model 3005 Plant Water Status Console (Soil Moisture Equipment Corp., Santa Barbara, CA) with the cut edge of the petiole facing outwards. With the leaf sealed within the chamber, the pressure was slowly increased using a portable nitrogen gas cylinder until sap emerged from the cut edge of the petiole. At this point, the gas flow was stopped and the corresponding pressure retained within the chamber was recorded. Measurements were made in negative bar units (10 bars = 1 MPa).

2.2.3 Harvest and yield components

During the autumn of both 2010 and 2011, all vineyard blocks were harvested in cooperation with vineyard managers. Grapes were hand harvested from each sentinel vine, with yield and clusters per vine recorded. Berry samples (100 berries) were also collected randomly from each experimental vine. These samples were stored at -25˚C until analysis. Additionally, 250-berry samples were retained from the smaller subset of vines in each of the Riesling blocks for the determination of free and potential volatile terpenes.

In February/March of each year following bud sampling, the vines were pruned based on the corresponding training system. Cane pruning weights were collected separately from each vine and weighed on site using a digital scale to determine vine size.

2.2.4 Laboratory analysis

i) Basic berry composition

The frozen berry samples were weighed, and then thawed at 80˚C in a water bath (Fisher Scientific Isotemp 228, Fisher Scientific, Mississauga, ON) for one hour to dissolve any precipitated tartrates. Samples were allowed to settle and cool to room temperature and were then juiced in an Omega 500 fruit juicer. The resulting juice was carefully separated from the lighter particulate matter. The pH (Accumet pH meter, model 25; Denver Instrument Company, Denver, CO) and Brix (Abbé refractometer, model 10450; American Optical, Buffalo, NY) of the juice was then obtained. For Cabernet franc samples, a portion of the juice was set aside and centrifuged with a Model B-20 centrifuge (International Equipment Co. Needham Heights, MA) at 4 ^{o}C and 10,000 rpm for 10 minutes. The resulting supernatant was stored at -25˚C for further analysis of color intensity, anthocyanins and total phenols.

After pH and Brix determination, the Riesling and Cabernet franc juice was centrifuged at 4000 rpm for 10 minutes in an IEC Centra CL2 (International Equipment Company, Needham Heights, MA) centrifuge to remove debris. The titratable acidity (TA) of the supernatant was then measured with a PC-Titrate autotitrator (Man-Tech Associates, Guelph, ON) by titration with 0.1N NaOH to an end point of pH 8.2. Before running the samples through the autotitrator, three water blanks and three standard solutions of tartaric acid were run to condition the instrument and calibrate the samples. At the end of the sample run, standards and blanks were repeated to account for drift during the analysis period.

ii) Monoterpene analysis

Monoterpenes were analyzed for the 250-berry Riesling samples using the distillation method developed by Dimitriadis and Williams (1984), as modified by Reynolds and Wardle (1989). Duplicate samples were prepared and run simultaneously on two distillation apparati. Upon collection of the 25-mL and 50-mL distillates, samples were covered and stored for no more than 5 days in a 4 ^{o}C refrigerator. Modifications of the methods stated above were made including mixing of the samples and vanillin solution in incubation tubes to provide a safer method by which to mix the samples. In addition, percent recovery analyses were also conducted by performing a standard addition of 10 mg/kg to a 100-g solution of homogenized Riesling grapes. The free volatile terpene (FVT) and potentially-volatile terpene (PVT) concentrations were expressed in mg/kg.

iii) Colour and hue analysis

Cabernet franc samples were removed from storage at -25 ^{o}C and thawed in a water bath at 80^{o}C for 30 minutes. After cooling to room temperature, color, anthocyanins and total phenols were determined for each berry sample. Color intensity and hue were determined using a modified method provided by Mazza et al. (1999). Juice samples were diluted appropriately with pH 3.5 buffer within 3.5-mL plastic cuvettes to a final volume of 2 mL. The pH 3.5 buffer was also used as a blank while distilled water was used to zero the spectrometer. Colour intensity and hue were calculated from absorbance values measured at 420 nm and 520 nm on an Ultrospec 2100 Pro UV/VIS spectrophotometer (Biochrom Ltd., Cambridge, UK). The following equations were used to calculate colour and hue:

$$(1)\ \text{Colour intensity} = A_{520nm}+A_{420nm}$$

$$(2)\ \text{Hue} = A_{420nm}/A_{520nm}$$

(iv) Anthocyanin analysis

Total anthocyanins concentration in berries was determined using the pH shift method, a modified version of the procedure of Fuleki and Francis (1968). The pH 1.0 and pH 4.5 buffer solutions were prepared using 0.2M KCl with 0.2M HCl, and 1M sodium acetate with 1M HCl in distilled water, respectively. Each juice sample (100 µL) was diluted with buffer to 2 mL within a 3.5-mL plastic cuvette. This procedure was completed once for each respective buffer. The samples were then mixed well and held in the dark for one hour. After one hour, the absorbance was measured at 520 nm using a Biochrom Ultrospec 2100 pro UV/Vis spectrometer (Cambridge, UK) using the appropriate buffer solution as a blank. The total anthocyanins concentration was calculated with the following formula:

$$(3)\ \text{Total anthocyanins (mg/L)} = A_{520}\ (\text{pH } 1.0 - \text{pH } 4.5)\ \text{X}\ 255.75$$

As a modification to the method, a calibration curve was completed using malvidin-3-glucoside standards with a molecular weight of 255.75 g/mol. Once adjusted with the calibration curve, sample measurements were corrected by applying the appropriate dilution factor.

(v) Total phenols analysis

The concentration of total phenols was determined by colorimetric measurement of the blue color caused by the redox reaction between reductant phenols and oxidant Folin-Ciocalteu reagent (VWR, West Chester, PA) in an alkaline solution of sodium carbonate using the method developed by Singleton and Rossi (1965) and adapted for smaller volumes by Waterhouse (2001). Calibration standards were prepared by adding 0, 1, 2, 3, 5 and 10 mL of 5 g/L gallic acid stock solution to 100-mL volumetric flasks and diluting with distilled water to obtain 0, 50, 100, 150, 250, and 500 mg/L standards. These were used to create a standard curve to calculate the total phenols in the Cabernet franc berry samples, which were expressed in mg/L gallic acid equivalents (GAE). The berry juice samples were diluted tenfold with distilled water to a final volume of 10 mL. The samples and standards alike (20 μL) were transferred to 3.5-mL plastic cuvettes. To this, 100 μL of Folin-Ciocalteu reagent was added to each and mixed. The solutions were then allowed to sit for 30 seconds to 8 minutes before adding 300 μL of 200 g/L $NaCO_{3.}$ Samples were mixed again and allowed to sit for 2 hours before recording their absorbance at 765 nm. Samples were prepared in groups of 30 to 40 cuvettes in order to perform the analysis within the time constraints.

2.2.5 Statistics procedures

Statistical analysis of the data was performed with XLStat (2012 version, Addinsoft SARL, New York, NY). Each variable was first checked for normality and errors before completing any other procedures, as Pearson's correlation and linear regression tests are parametric in nature and thus require normal data distributions where possible regardless of the nature of the data (Warner 2008, Zuur et al. 2010). In addition, the spatial interpolation of data using GIS programs often requires knowledge and adjustment of data distributions in order to produce accurate maps (Bramley and Hamilton 2004, Bramley et al. 2011, de Smith et al. 2007, McKinion et al. 2010, Zhang et al. 2011). For those sites which displayed a great many variables with non-normal distributions, histograms were plotted to observe the data trends. Further normality tests were also completed upon filtering of the data for principal components analysis (PCA) and multilinear regression. When a large number of non-normal distributions still occurred, efforts were made to remove extreme data points skewing the distributions. After checking for normality, two separate correlation tests were performed: i) correlations between water metrics, fruit composition, vine size, bud survival, and mean bud LT_{50}, and ii) correlations between water metrics, monthly and mean bud LT_{50}, vine size, and bud survival. The choice was made to split the data into two groups, as too many variables in a single correlation test with a limited number of data points can lead to Type I error (Warner 2008). Two variables, “cluster number” and “hue”, which were highly correlated (p-value < 0.0001) to yield and phenolic analytes respectively, were removed in order to limit strong cases of co-linearity. Other variables were also reviewed carefully for co-linearity, which can compromise the results of many statistical tests (including PCA and multilinear regression) by over-representing closely related variables and under-representing the possibly important relationships of those remaining (Warner 2008).

In order to perform PCA and to account for the greatest amount of variability within the data, k-means clustering analysis was performed. K-means clustering analysis and other clustering methods have been used to compress data, uncover natural clustering in the data, and strengthen pre-existing relationships between variables (Bramley 2005, Bramley and Hamilton 2004, Bramley et al. 2011, Erdogan et al. 2009, McKinion et al. 2010). It was determined that three clusters should be identified with clustering analysis. The use of three clusters facilitates comparisons between the work contained in this thesis with research done during the same sampling years on low, medium, and high yield levels. The arbitrary number of clusters chosen is a large flaw in the procedure (de Smith et al. 2007). However, given the relatively small dataset this was believed to be an appropriate number. Clustering was performed on the data subset (mean bud LT_{50}). Data points which were not represented by every variable were excluded from the subset. Variables previously determined to be unnecessary were also not included in the subset. PCA was used to illustrate the interactions between large numbers of variables in a data set as these cannot always be illustrated fully within bivariate correlation tables. PCA was run using the cluster means. In all cases, 100% explained variability was achieved using two components. This suggests that all of the variability within the data has been accounted for and that the PCA diagrams accurately represent the relations between the variables. Relationships described by PCA were considered strong if their values were greater than 0.800 or less than -0.800.

Temperature and precipitation data was obtained from Environmental Canada at the Vineland Research Station, with mean monthly values plotted for the study period of June 2010 to March 2012. Although this is not central to all the blocks studied, it presents a general visualization of the weather patterns of the area (Fig. A22).

2.2.6 GIS mapping procedures

The GIS (geographic information system) program ArcGIS 10.1 [Environmental Systems Research Institute (ESRI), Redlands, CA] was used for all mapping procedures. Data were imported into ArcGIS from Microsoft Excel. The latitude and longitude measurements were first displayed in the geographic coordinate system NAD (North American Datum) 1983. The coordinates were then projected from NAD 1983 to NAD UTM (Universal Transverse Mercator) Zone 17N. The environments of the map interface were also set to ensure that all interpolations were projected to the same spatial extent and raster resolution. Data were interpolated using the (simple) kriging method in order to transform the variables from point data to raster data. The interpolations chosen had the lowest error values. Interpolations were rejected upon significant bulleting or other irregular geometric patterns. All interpolations were classified with 10 equal intervals and were displayed to a 2-m resolution. This was chosen in order to account for both human error and the accuracy of the GPS receiver and has been used previously in other *terroir* studies (Bramley 2005, Bramley and Hamilton 2004, Bramley et al. 2011).

2.3 Results

Chapter 2 results focus on the berry and vine relationships of water metrics (soil moisture and leaf ψ) and yield. Relationships between these three variables and bud hardiness or survival are described in *Chapter 4*. Two statistical methods were used to explore the relationships between water metrics (soil moisture and leaf ψ) and yield with other vine and berry characteristics. Pearson’s correlation tables were completed and are summarized in Tables A2 to A5 in the Appendix. When significant relationships occurred between soil moisture, leaf ψ, and yield, scatter plots are provided. Principal component analysis (PCA) was also completed after clustering of the data. PCA diagrams are given for each site for both 2010 and 2011.

2.3.1 Weather patterns

In 2010, the growing season was warm, with average temperatures of ≈20 ^{o}C from June to September (Fig. A19). High amounts of precipitation occurred in June (≈120 mm), with moderate rainfall from July to November (≈60 mm) (Fig. A20). Autumn temperatures decreased from an average of 15 ^{o}C in September to 5 ^{o}C in November. The dormant (winter) season of 2010/2011 was characterized by low average temperatures (below 0 ^{o}C from December to February) and high snowfall amounts, specifically in February when ≈60 mm of precipitation was recorded. It was also observed during winter field analysis that period of extreme cold (< -20 ^{o}C) were numerous and accounted for high instances of vine damage.

In 2011, the temperatures during the growing season were comparable with 2010 (Fig. A19). However, high amounts of precipitation fell prior to the start of the growing season (Fig. A20). Approximately 120 mm of precipitation was recorded in April while ≈160 mm was recorded in May. June and July were relatively dry (< 60 mm), while precipitation again increased in August (≈80 mm), September (≈120 mm), October (≈80 mm), and November (≈120 mm). Temperatures in the fall were comparable to 2010. The dormant season of 2011/2012 had above average temperatures, with the average in both December and February being above 0 ^{o}C. February recorded an average temperature just below the freezing mark. High amounts of rain (≈60 mm) fell in January.

2.3.2 Cabernet franc

No yield or berry composition data was collected for Lambert (2010). Correlation tests (Table A2) suggest that in 2010 soil moisture was negatively correlated with yield (two of five blocks), positively correlated with Brix (two of five blocks), and positively correlated with phenols (two of five blocks). In 2011, soil moisture was negatively correlated to Brix (two of six blocks) and colour (two of six blocks). When reviewing both years, the strongest correlation occurred between soil moisture and colour (negatively correlated to three of 11 blocks). Regarding PCA results (Figs. 2.1, 2.3, 2.4, 2.8, 2.9, and Fig. 2.11), in 2010 soil moisture was negatively related to berry weight (two of five blocks) and positively related to both Brix (four of five blocks) and phenols (two of five blocks). These results did not agree with the PCA run for all sites in 2010 (Fig. 2.13). In 2011, soil moisture was positively related to berry weight (three of six blocks), TA (two of six blocks), and vine size (three of six blocks). It was also negatively related to phenols (three of six blocks) and leaf ψ (two of six blocks). With the exceptions of berry weight and phenols, these results did not agree with the PCA run for all sites in 2011 (Fig. 2.13). When reviewing years, soil moisture was positively related to Brix (five of 11 blocks), TA (four of 11 blocks), and vine size (three of 12 blocks). It was also negatively related to leaf ψ (four of 12 blocks). When comparing the correlation and PCA results, no common variables were found; more relationships were found using PCA. In general, low soil moisture was linked with high colour (correlation tests), low Brix, TA, and vine size, and high leaf ψ (PCA results). Vineyard blocks displaying these relationships include: Kocsis 2010/2011 (Fig. 2.25 and Fig. A3), and Cave Spring 2010/2011 (Fig. 2.27, Fig. 2.30, and Fig. A5).

Correlation tests (Table A2) suggest that in 2010 leaf ψ was positively correlated to berry weight (two of five blocks) and vine size (three of six blocks). In 2011, leaf ψ was positively correlated to TA (two of six blocks) and vine size (two of six blocks). When reviewing both years, strong correlations appeared between leaf ψ and berry weight (three of 11 blocks), TA (three of 11 blocks), and vine size (five of 12 blocks). Regarding PCA results (Figs. 2.1, 2.3, 2.4, 2.8, 2.9, and Fig. 2.11), in 2010 leaf ψ was positively associated with yield (two of five blocks), and negatively associated with both Brix (three of five blocks) and TA (two of five blocks). As with soil moisture, these results did not agree with the PCA run for all sites in 2010 (Fig. 2.13). In 2011, leaf ψ was linked with more variables which included positive relationships with yield (two of six blocks) and TA (two six blocks), and negative relationships with Brix (three of six blocks), phenolic analytes (anthocyanins – three of six blocks, colour – two of six blocks, and phenols – two of six blocks), soil moisture (two of six blocks), and vine size (two of six blocks). When compared to the PCA run for all sites in 2011 (Fig. 2.13), many relationships were not the same. However, leaf ψ was found to be negatively related to Brix and phenolic analytes, as in the other PCAs. When reviewing both years it was found that leaf ψ was positively associated with yield (four of 11 blocks), and negatively associated with Brix (six of 11 blocks), phenolic analytes (five, four, and three blocks, respectively), soil moisture (four of 12 blocks), and vine size (five of 12 blocks). When comparing the correlation and PCA results, vine size was related to leaf ψ in both. However, this relationship was inversely related between the tests. In general, low leaf ψ was related to low berry weight, TA, and vine size (correlation results). It was also linked with low yield and high Brix, phenolic analytes, soil moisture, and vine size. Blocks displaying these relationships include: George 2010/2011 (Figs. 2.24, 2.29, 2.30, and A2), Kocsis 2010/2011 (Figs. 2.25, 2.29, 2.30, and A3), and Lambert 2011 (Figs. 2.26, 2.30, and A4).

For yield, correlation tests (Table A3) revealed more relationships than soil moisture and leaf ψ. In both 2010 and 2011, yield was positively correlated with berry weight (six of 11 blocks) and vine size (six of 11 blocks). It was also negatively correlated with Brix (eight of 11 blocks), anthocyanins (six of 11 blocks), colour (seven of 11 blocks), and phenols (seven of 11 blocks). Additionally, in 2010, yield was negatively correlated with pH (two of five blocks) and soil moisture (two of five blocks). Regarding PCA results (Figs. 2.1, 2.3, 2.4, 2.8, 2.9, and Fig. 2.11), in 2010 yield was positively related with berry weight (three of five blocks), leaf ψ (two of five blocks), and vine size (three of five blocks). It was also negatively related to TA (three of five blocks) and soil moisture (two of five blocks). As with soil moisture and leaf ψ, these results did not agree with the PCA run for all sites in 2010 (Fig. 2.13). In 2011, yield was again positively linked with berry weight (three of six blocks). It was also positively linked with pH (three of six blocks), and leaf ψ (four of six blocks). It was negatively associated with Brix (two of six blocks) and phenolic analytes (two, three, and four blocks, respectively).When compared to the PCA run for all sites in 2011 (Fig 2.13), the relationships between yield and Brix, and yield and phenolic analytes was supported (Fig. 2.13).When reviewing both years it was found that yield was positively associated with berry weight (six of 1` blocks), pH (four of 11 blocks), leaf ψ (four of 11 blocks), and vine size (six of 11 blocks). It was also negatively associated with Brix (four of 11 blocks), TA (four of 11 blocks), and phenolic analytes (three, four, and four of 11 blocks, respectively). All of the correlation results discussed were supported by the PCA results. In general, low yield was related to low berry weight, pH, leaf ψ, and vine size. Low yield was also associated with high Brix, TA, and phenolic analytes. Vineyard blocks displaying these relationships include: Buis 2010/2011 (Figs. 2.23, 2.29, 2.30, and A1), George 2010/2011 (Figs. 2.24, 2.29, 2.30, and A2), Kocsis 2010/2011 (Figs. 2.25, 2.29, 2.30, and A3), Cave Spring 2010/2011 (Figs. 2.27, 2.29, 2.30, and A5), and Lowrey 2010/2011 (Figs. 2.28, 2.29, 2.30, and A6).

In summary, lower water status and yield were often associated with lighter berries, higher Brix, and higher phenolic analytes (anthocyanins, colour, and phenols). Soil moisture displayed inconsistent patterns between years, possibly as a result of weather patterns, with 2011 having a wetter spring and fall. Often it was difficult to determine consistent relationships with vine size. Individual block results agreed somewhat with the PCA run for all sites. However, differences between the PCA of all sites and the other PCA results did arise when reviewing the six blocks as a whole. Therefore, it is possible that while k-means clustering with three clusters was appropriate for individual blocks, this same method may not have been effective when considering all the blocks at once. Correlations between soil moisture, leaf ψ, and yield occurred for Buis 2011 ($R^2 = 0.2103$, Fig. 2.2), Kocsis 2010 and 2011 (Fig. 2.5 to Fig. 2.7; $R^2 = 0.2805$, $R^2 = 0.2645$, $R^2 = 0.354$, respectively), Cave Spring 2010 ($R^2 = 0.1069$, Fig. 2.10), and Lowrey 2010 ($R^2 = 0.2105$, Fig. 2.12). Soil moisture and leaf ψ were not correlated to each other for any block or year.

2.3.3 Riesling

Correlation tests (Table A4) suggest that in 2010 soil moisture was negatively correlated to pH in three of the six blocks studied. No other apparent relationships were found in the blocks. In 2011, soil moisture was negatively correlated with TA (two of six blocks). When reviewing both years, soil moisture was negatively correlated with pH (three of 12 blocks). Regarding PCA results (Figs. 2.14, 2.15, 2.16, 2.18, 2.19, and 2.21) in 2010 soil moisture was positively associated with Brix (four of six blocks) and negatively associated with vine size (four of six blocks). No similarities were found when comparing these results to the PCA of all Riesling blocks in 2010 (Fig. 2.22). In 2011, soil moisture was positively associated with TA (two of six blocks) and negatively associated with berry weight (three of six blocks). No relationships were found for soil moisture for the PCA of all Riesling blocks (Fig. 2.22). When reviewing both years, it was found that soil moisture was positively associated with Brix (five of 12 blocks) and monoterpenes (three of 12 blocks), and was negatively associated with berry weight (four of 12 blocks). When comparing the correlation and PCA results, no similarities were found, with the PCA results identifying more relationships. In general, low soil moisture was related to high pH (correlation tests), high berry weight, low Brix, and low monoterpenes (PCA). Vineyard blocks displaying these relationships include: George 2010 (Figs. 2.32 and A14), Hughes 2010/2011 (Figs. 2.33, 2.38, and A15), and Lowrey 2010/2011 (Figs. 2.36, 2.37, and A18).

Correlation tests (Table A4) suggest that in 2010 leaf ψ was positively correlated with berry weight (two of six blocks). In 2011, leaf ψ was positively correlated with Brix (two of six blocks) and negatively correlated with TA (two of six blocks). When reviewing both years, it was found that leaf ψ was positively correlated with berry weight (four of 12 blocks) and Brix (three of 12 blocks), and negatively correlated with TA (three of 12 blocks). Regarding PCA results (Figs. 2.14, 2.15, 2.16, 2.18, 2.19, and 2.21), in 2010 leaf ψ was found to be positively related to berry weight (two of six blocks), TA (three of six blocks), and vine size (two of six blocks), and negatively related to Brix (four of six blocks). In 2011, similar relationships were found for berry weight (four of six blocks) and Brix (four of six blocks). The opposite relationship was found for vine size (two of six blocks). In addition, leaf ψ was positively associated with yield (two of six blocks) and negatively associated with monoterpenes (three of six blocks). These results are in good agreement with the PCAs done for all sites (Fig. 2.22) where leaf ψ has a positive association with berry weight and TA, and a negative association with Brix in 2010, and reveals the same relationships between leaf ψ and yield, berry weight, and Brix in 2011. When reviewing both years, it was found that leaf ψ was positively associated with berry weight (six of 12 blocks) and TA (five of 12 blocks), and negatively associated with Brix (eight of 12 blocks), monoterpenes (four of 12 blocks), and soil moisture (three of 12 blocks). When comparing the correlation and PCA results, leaf ψ was positively related to berry weight for both. However, the tests showed inversed relationships for Brix and TA. As such, in general, low leaf ψ was related to low berry weight, high monoterpenes, and high soil moisture. Vineyards displaying these relationships include: George 2010/2011 (2.32, 2.37, 2.38, and A14), Hughes 2010/2011 (Figs. 2.33 and A15), and Cave Spring 2010/2011 (Figs. 2.35 and A17).

Correlation tests (Table A5) suggest that in 2010 and 2011, yield was negatively correlated with Brix (five of 12 blocks) and pH (four of 12 blocks). It was also positively correlated with vine size for both years (six of 12 blocks). Other strong relationships over both years include positive correlations with berry weight (three of 12 sites, primarily in 2010), and negative correlations with TA (three of 12 blocks, primarily in 2011). Regarding PCA results (Figs. 2.14, 2.15, 2.16, 2.18, 2.19, and 2.21), yield did not show any significant relationships in 2010. Over both 2010 and 2011 (and primarily in 2011), it was positively associated with berry weight (five of 12 blocks), Brix (three of 12 blocks), and vine size (five of 12 blocks). These relationships were in partial agreement with the PCA for all sites for 2011 (Fig. 2.22). When comparing the correlation and PCA results, all of the PCA relationships outlined above (berry weight, Brix, vine size) were corroborated by the correlation results. In general, low yield is linked with low berry weight and vine size, as well as high pH, high Brix, and high TA. Vineyards displaying these relationships include: Buis 2010/2011 (Figs. 2.31 and A13), Lambert 2010/2011 (Figs. 2.34 and A16), and Lowrey 2011 (Figs. 2.36 and A18).

In summary, leaf ψ, and yield were often positively associated with one another. Lower water status and yields were often associated with lighter berries, higher Brix, and higher pH. As with Cabernet franc blocks, soil moisture was not always in agreement with leaf ψ and yield as it was often positively associated with Brix and negatively associated with berry weight. Contradictory relationships between vine size and soil moisture, and vine size and leaf ψ were seen between sites. However, high yield was often linked to high vine size. The same can be said for relationships with TA and monoterpenes. Few correlations were found for any sites. PCA results yielded more information than correlations. Individual block results were in good agreement with the PCA for all sites.

2.4 Discussion

It was initially hypothesized that soil moisture, leaf ψ, and yield would be associated with one another. It was also hypothesized that these variables would be related to berry composition - specifically that low soil moisture, leaf ψ, and yield would result in lower berry weights and higher values of Brix, phenolic analytes, and monoterpene concentrations. For the Cabernet franc blocks (Buis, George, Kocsis, Lambert, Cave Spring, and Lowrey) and Riesling blocks (Buis, George, Hughes, Lambert, Cave Spring, and Lowrey), these hypotheses were mostly supported. Comparing Figs. A1-A6 and Figs. A13-A18, relationships between soil moisture, leaf ψ, and yield were indeed found. In general, leaf ψ was directly related to yield – lower leaf ψ and thus greater potential water stress promoted lower yields, a result supported in literature (Mazza et al. 1999, Roby et al. 2004, van Leeuwen and Seguin 2006). However, not all blocks were in agreement with this statement over both years, particularly Riesling blocks in 2011 (Figs. A14, A16, A17, and A18). This trend may be due to the weather during the 2011 growing season which was uncharacteristically hot and dry during peak summer months but cold and wet in both the spring and fall. Therefore low leaf ψ values would be recorded in the summer but would not reflect berry expansion in the fall. Additionally, vines with high yields can self-impose water stress due to metabolic demands, thus recording lower leaf ψ values (Acevedo-Opazo et al. 2008, Acevedo-Opazo et al. 2010, Koundouras et al. 2006, Keller and Mills 2007).

Relationships between soil moisture and both leaf ψ and yield were often indiscernible or negative in nature; this pattern was also seen when investigating berry composition relationships. It has been suggested that inverse relationships of this nature arise because of high evapotranspiration rates and vine vigour in relation to soil moisture levels - unbalanced vines showing symptoms of water stress due to high vegetative growth (Koundouras et al. 2006, Shaw 2005, Sivilotti et al. 2005). Further complications with soil moisture may have arisen due to the heterogeneous nature of Niagara Peninsula soil, as soil types may differ in their ability to supply both water and nutrients. Heavy clay soils, for instance, hold greater amounts of water than soils with more sand or silt (compare Kocsis, Fig. A3 with Buis, Fig. A1; Koundouras et al. 2006, Seguin 1986). This may water log the vines and lead to a decrease in leaf ψ. Decreased access to dissolved oxygen and nutrients in these soils may also be a hindrance to proper vine growth and development, thus leading to lower leaf ψ and yield. Issues regarding soil moisture relationships may also be a result of root depth, since soil water availability relies heavily on this (Seguin 1986, Koundouras et al. 2006). Water accessed by vines may have been deeper than the field instrumentation would be able to measure. Therefore, measurements may not have accurately represented soil water availability. Additionally, relationships with leaf ψ and soil moisture may have been improved by recording pre-dawn leaf ψ measurements instead of midday leaf ψ since pre-dawn measurements are assumed to be more precisely related to soil moisture (Williams and Araujo 2002). However, pre-dawn leaf ψ was not practical to collect for this study. Vine size revealed inconsistent results for both Cabernet franc and Riesling, similar to the situation for soil moisture. These results are supported by previous work which has shown that relationships with vine size are inconsistent and vary spatially over a region (Ledderhof 2011, Reynolds et al. 2007, Reynolds et al. 2010a). It is likely that the values measured were inaccurate representations of vine size due to field irregularities as a result of vineyard management strategies. However, it was noted that more vigorous vines could support higher yields, as with Buis and Kocsis Cabernet franc (Fig. A1, A3) and George and Lowrey Riesling (Fig. A14, A18). It is hypothesized that this is due to the environmental characteristics of these blocks, especially for Kocsis Cabernet franc (Fig. A3) and Lowrey Riesling (Fig. A18), which were located in high clay soils and warm sites, respectively – environmental conditions which can cause additional stress to the vines. Therefore, vines which were placed in more favourable growing conditions within these blocks would have a greater vine size and would be able to support higher yields.

The second hypothesis that low soil moisture, leaf ψ, and yield would result in high berry composition values was supported for both Cabernet franc and Riesling. In literature, low water metrics and yields are often associated with smaller berry size (lower berry weight), increased Brix, and increased concentrations of phenolic analytes for red varieties (Kennedy et al. 2002, Koundouras et al. 2006, Matthews and Nuzzo, 2007, Mazza et al. 1999, Ojeda et al. 2002, Roby et al. 2004, Shellie 2010, Sivilotti et al. 2005, van Leeuwen and Seguin 2006). This study revealed the same results, with areas of low leaf ψ and yield being spatially related to smaller berries and higher Brix measurements (Figs. A1, 2.28). Particularly strong relationships were found regarding anthocyanin concentrations (Figs. A1, A2, A3, A4, A5 and A6 compared to Fig. 2.29 and 2.30). It is suspected that increases in the concentrations of solutes are not directly related to decreases in berry size but are instead parallel processes that occur in vines experiencing moderate water stress (Matthews and Nuzzo 2007, Ojeda et al. 2002, Roby et al. 2004, Shellie 2010). A good representation of all of these relationships is displayed by the

George Cabernet franc maps in both 2010 and 2011 (Figs. A2, 2.24, 2.29, and 2.30). However, these maps do reveal uncertainties concerning pH and TA; this is not unusual, as other studies have also reported inconsistent relationships with these variables (Acevedo-Opazo et al. 2010, Koundouras et al. 2006, Sivilotti et al. 2005).

In the Riesling blocks soil moisture variation was not consistent with any of the hypothesized relationships. For instance, low soil moisture often led to high berry weight, low Brix, low pH, and low monoterpene concentrations. Monoterpene relationships were particularly intriguing since yield was also positively associated with this family of flavour compounds, while low leaf ψ produced high monoterpene concentrations (see interpolations found in Fig. A13-A18, and 2.36 and 2.37). This suggests that high monoterpene concentrations were related to high soil moisture, high yield, high berry weight, and low leaf ψ. Previous research has also found that monoterpene concentrations increased with lower leaf ψ and berry weight (Reynolds et al. 2010a, Reynolds et al. 2010b). Issues regarding the role of monoterpenes have previously been mentioned by Reynolds and Wardle (1989) and Hornsey (2007), who reported misgivings as to the role of terpenes in the ripening process. Most commonly, terpenes are considered to increase continuously upon the onset of véraison, reaching peak concentrations prior to the plateau of Brix levels (Hornsey 2007). Unlike monoterpene concentrations, other berry composition variables such as berry weight, Brix, pH, and TA produced the expected relationships, as can be seen in Figs. 2.31-2.36 and Figs. A13-A18. Thus, as supported in literature, lower leaf ψ and yields produced smaller berries with higher Brix levels, higher pH, and lower TA (Reynolds et al. 2010a, Reynolds et al. 2010b, Shellie 2010, van Leeuwen and Seguin 2006).

In this study, the decision was made to use k-means clustering to group and analyze data. Although some of the relationships did not agree with the binary correlation results, the clustering technique coupled with PCA was successful in recognising important relationships between variables, as in other studies (Acevedo-Opazo et al. 2008, Acevedo-Opazo et al. 2010, Reynolds et al. 2010a, Reynolds et al. 2010b, Schlosser et al. 2005). As previously mentioned, k-means clustering is heavily used by Bramley et al. (2004, 2005, 2010). However, in these studies, efforts were made to apply these techniques spatially. Although this was beyond the scope of this study, it is recommended that further research be done into both spatially applied k-means clustering and PCA techniques, as mapping programs are strengthening their ability to run these and other multivariate statistics. However, for the sake of this study, the implementation of clustering and PCA through XLStat, with comparisons to correlation tests and kriging interpolations has produced satisfactory results.

2.5 Conclusions

In this chapter, it was hypothesized that soil moisture, leaf ψ, and yield would be associated with one another and with berry composition variables. In particular, it was expected that low soil moisture, leaf ψ, and yield would result in lower berry weights and higher values of Brix, phenolic analytes, and monoterpene concentrations. The data collected and analyzed in this study were generally supportive of the hypotheses of this chapter. Leaf ψ and yield were often directly related to one another, and were related to measurements of berry composition variables. Thus, areas of low leaf ψ and yield led to the production of smaller berries with greater concentrations of sugar and phenolic analytes for Cabernet franc blocks, and smaller berries with lower TA, higher pH, and higher Brix for Riesling blocks. However, unexpected patterns for soil moisture, vine size, and monoterpene concentrations were revealed. Soil moisture and vine size showed inconsistent relationships with variables studied, possibly due to the method of soil moisture measurements, vineyard variability, and vine management practices.

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2.7 List of Figures

Figure 2.31 Maps of berry weight, Brix, pH, and titratable acidity for the Buis Riesling block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

Figure 2.32 Maps of berry weight, Brix, pH, and titratable acidity for the George Riesling block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

Figure 2.33 Maps of berry weight, Brix, pH, and titratable acidity for the Hughes Riesling block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

Figure 2.34 Maps of berry weight, Brix, pH, and titratable acidity for the Lambert Riesling block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

Figure 2.35 Maps of berry weight, Brix, pH, and titratable acidity for the Cave Spring Riesling block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

Figure 2.36 Maps of berry weight, Brix, pH, and titratable acidity for the Lowrey Riesling block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

Figure 2.37 Maps of monoterpene concentrations in 2010. a) Buis, b) George, c) Kocsis, d) Lambert, e) Cave Spring, f) Lowrey.

Figure 2.38 Maps of monoterpene concentrations in 2011. a) Buis, b) George, c) Kocsis, d) Lambert, e) Cave Spring, f) Lowrey.

Supplemental Figures Relevant to this Chapter

Figure A1 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Buis Cabernet franc block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and vine size. Bottom row: 2011 soil moisture, leaf ψ, yield, and vine size. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 5.0833 (clustered), z-score = -1.9184 (dispersed), and z-score = 1.688 (clustered), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 5.7167 (clustered), z-score = 0.9589 (random), and z-score = 3.5343 (clustered), respectively.

Figure A2 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the George Cabernet franc block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 2.9434 (clustered), z-score = 1.9882 (clustered), and z-score =0.0659 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 0.9114 (random), z-score = 3.2365 (clustered), and z-score = 1.5283 (random), respectively.

Figure A3 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Kocsis Cabernet franc block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and vine size. Bottom row: 2011 soil moisture, leaf ψ, yield, and vine size. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 4.2432 (clustered), z-score = 0.2094 (random), and z-score = 2.2269 (clustered), respectively; Morans I results for

2011 soil moisture, leaf ψ, and yield are: z-score = 0.8474 (random), z-score = 0.3341 (random), and z-score = 1.3816 (random), respectively.

Figure A4 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Lambert Cabernet franc block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture and leaf ψ are: z-score = 3.0137 (clustered) and z-score = 1.5747 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 0.7463 (random), z-score = 2.5129 (clustered), and z-score = -0.6691 (random), respectively.

Figure A5 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Cave Spring Cabernet franc block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 3.3145 (clustered), z-score = -0.3773 (random), and z-score = 0.1508 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 2.5846 (clustered), z-score = 7.8715 (clustered), and z-score = 1.6823 (clustered), respectively.

Figure A6 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Lowrey Cabernet franc block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 1.6154 (random), z-score = -0.0988 (random), and z-score = -1.3836 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 1.0417 (random), z-score = -1.7254 (dispersed), and z-score = -0.9293 (random), respectively.

Figure A13 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Buis Riesling block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 2.8219 (clustered), z-score = -2.3459 (dispersed), and z-score = -0.1877 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 4.1285 (clustered), z-score = 0.5315 (random), and z-score = 1.0981 (random), respectively.

Figure A14 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the George Riesling block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 3.6332 (clustered), z-score = 1.2104 (random), and z-score = -0.3507 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 0.7377 (random), z-score = 1.8031 (clustered), and z-score = 2.1613 (clustered), respectively.

Figure A15 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Hughes Riesling block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 4.6690 (clustered), z-score = 4.6533 (clustered), and z-score = -1.0163 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 0.8497 (random), z-score = 4.2595 (clustered), and z-score = 1.2841 (random), respectively.

Figure A16 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Lambert Riesling block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and vine size. Bottom row: 2011 soil moisture, leaf ψ, yield, and vine size. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 3.5807 (clustered), z-score = 1.4994 (random), and z-score = 0.6064 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 1.1155 (random), z-score =-1.1223 (random), and z-score = 1.3798 (random), respectively.

Figure A17 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Cave Spring Riesling block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 1.7576 (clustered), z-score = -1.5457 (random), and z-score = 0.7432 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 1.1309 (random), z-score = 0.7948 (random), and z-score = -0.2777 (random), respectively.

Figure A18 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Lowrey Riesling block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 3.1555 (clustered), z-score = -0.9960 (random), and z-score = 0.8420 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 0.1320 (random), z-score = 1.3239 (random), and z-score = 1.1966 (random), respectively.

Figure A19 Mean monthly temperatures at Vineland Research Station for June to December 2010 (black), January to December 2011 (white), and January to March, 2012 (grey).

Figure A20 Mean monthly precipitation at Vineland Research Station for January to December 2010 (black), January to December 2011 (white), and January to March, 2012 (grey).

Figure A22 Map of the Niagara wine region. Red circles represent Cabernet franc research blocks, green circles represent Riesling research blocks, and “+” represents the Vineland Research weather station. From left to right, Cabernet franc blocks are Cave Spring, Kocsis, George, Buis, Lambert, Lowrey; from left to right, Riesling blocks are Cave Spring, Hughes, George, Lambert, Buis, and Lowrey. Map courtesy of the Vintners Quality Alliance (VQA).

2.8 Figures

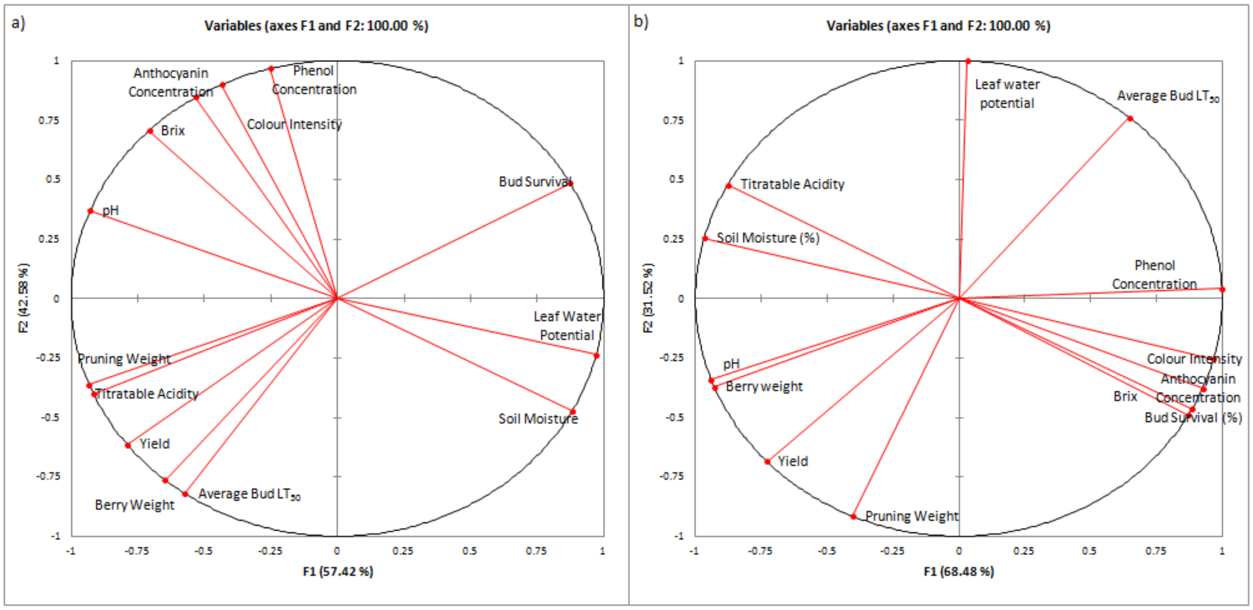

Figure 2.1 Principal component analysis diagrams of the Buis Cabernet franc vineyard block for a) 2010 and b) 2011. Variables include berry composition, vine characteristics, and winter hardiness characteristics. PCA was run with three clusters and two factors.

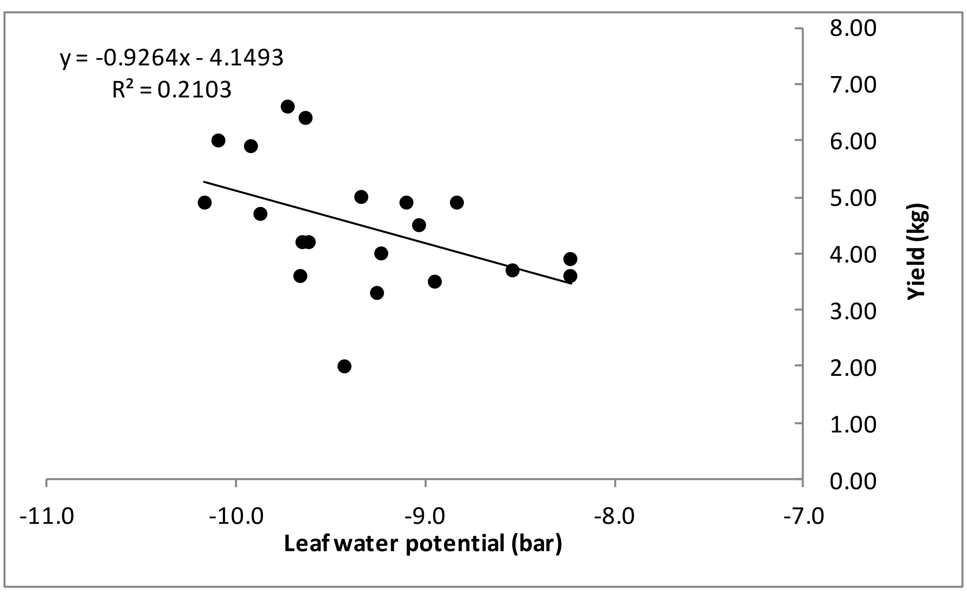

Figure 2.2 Yield vs. Leaf water potential scatter-plot for the Buis Cabernet franc block in 2011.

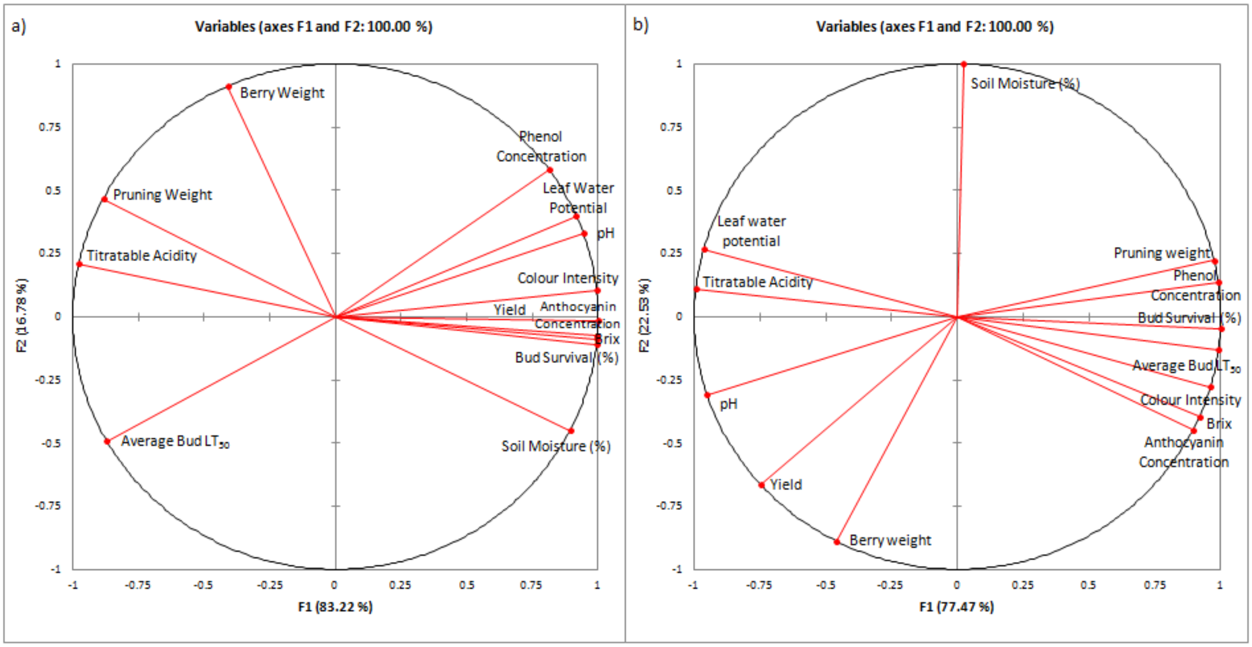

Figure 2.3 Principal component analysis diagrams of the George Cabernet franc vineyard block for a) 2010 and b) 2011. Variables include berry composition, vine characteristics, and winter hardiness characteristics. PCA was run with three clusters and two factors.

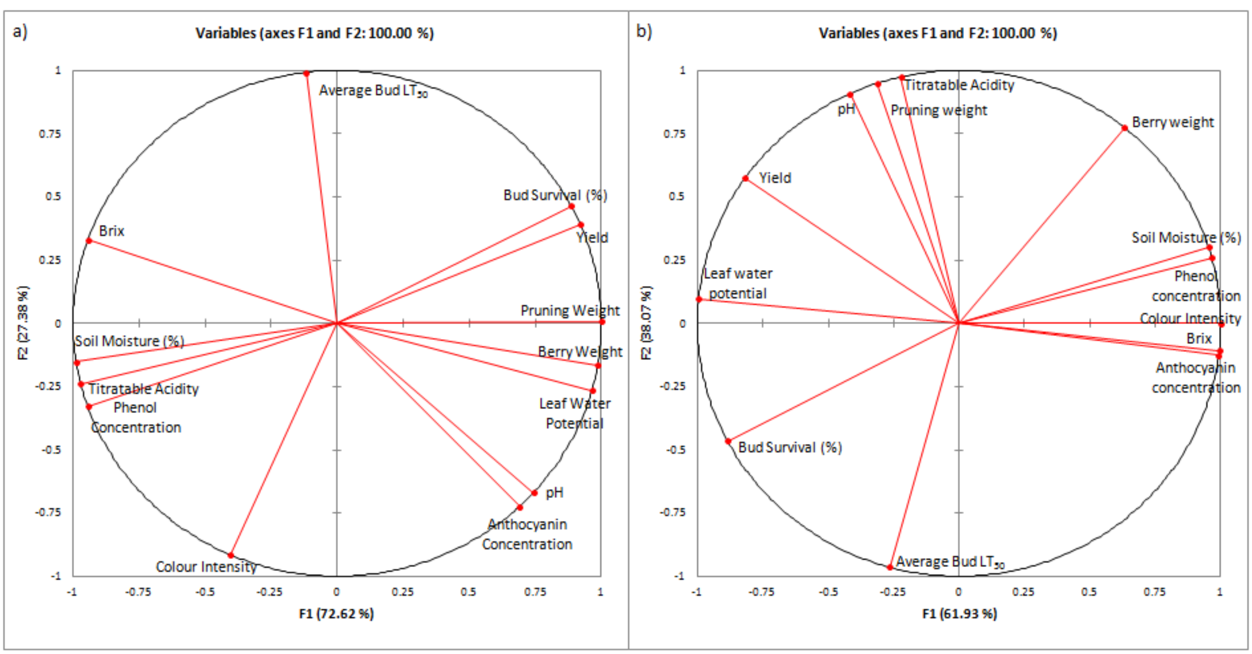

Figure 2.4 Principal component analysis diagrams of the Kocsis Cabernet franc vineyard block for a) 2010 and b) 2011. Variables include berry composition, vine characteristics, and winter hardiness characteristics. PCA was run with three clusters and two factors.

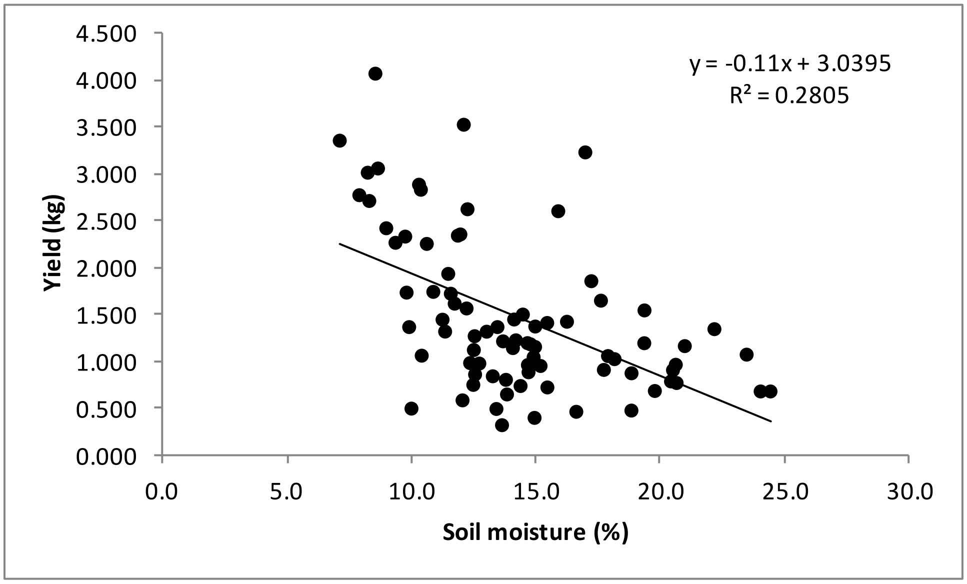

Figure 2.5 Yield vs. soil moisture scatter-plot for the Kocsis Cabernet franc block in 2010.

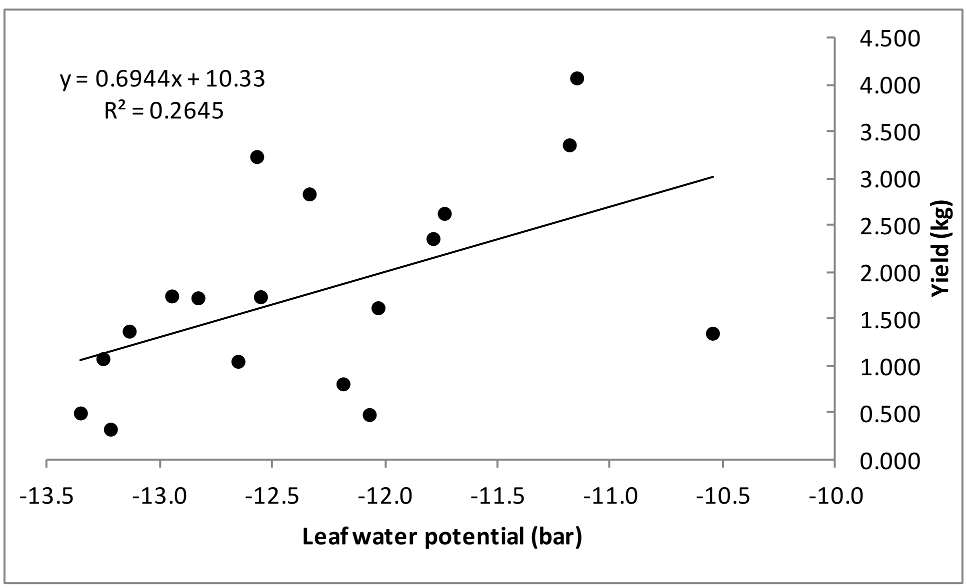

Figure 2.6 Yield vs. Leaf water potential scatter-plot for the Kocsis Cabernet franc block in 2010.

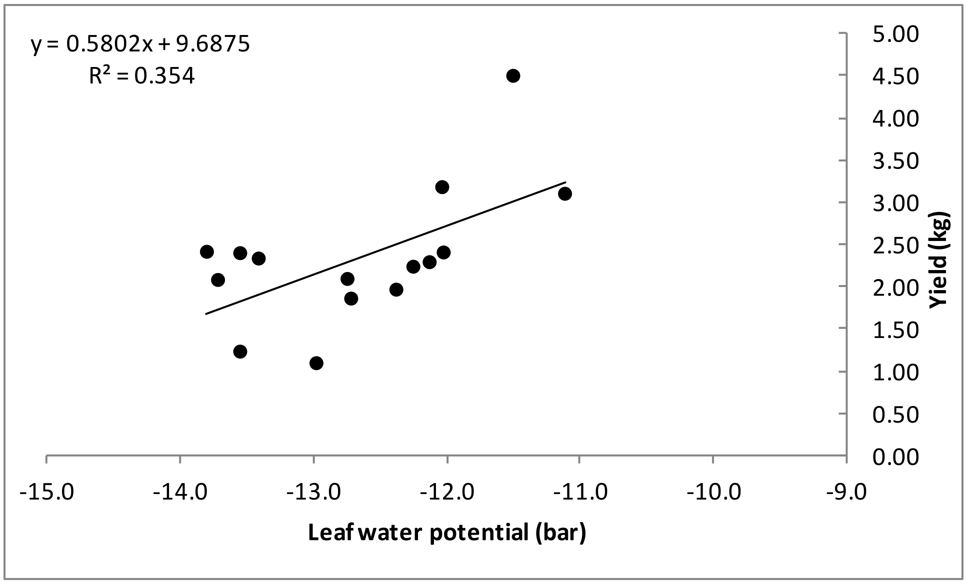

Figure 2.7 Yield vs. Leaf water potential scatter-plot for the Kocsis Cabernet franc block in 2011.

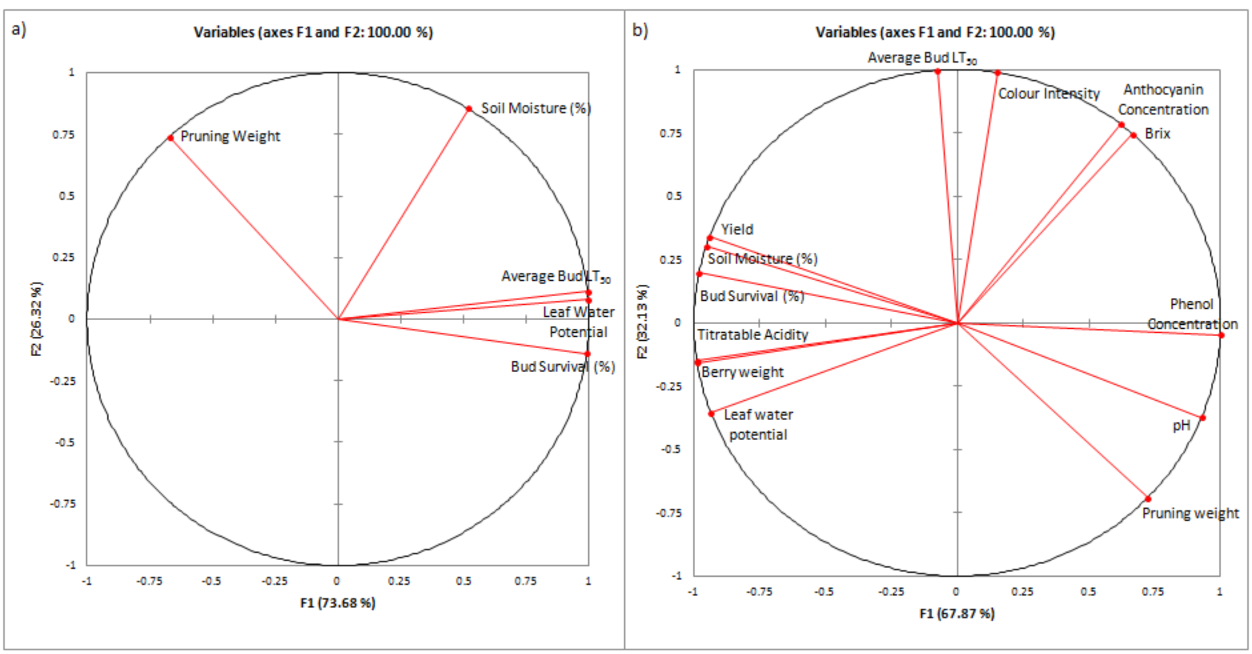

Figure 2.8 Principal component analysis diagrams of the Lambert Cabernet franc vineyard block for a) 2010 and b) 2011. Variables include berry composition, vine characteristics, and winter hardiness characteristics. PCA was run with three clusters and two factors.

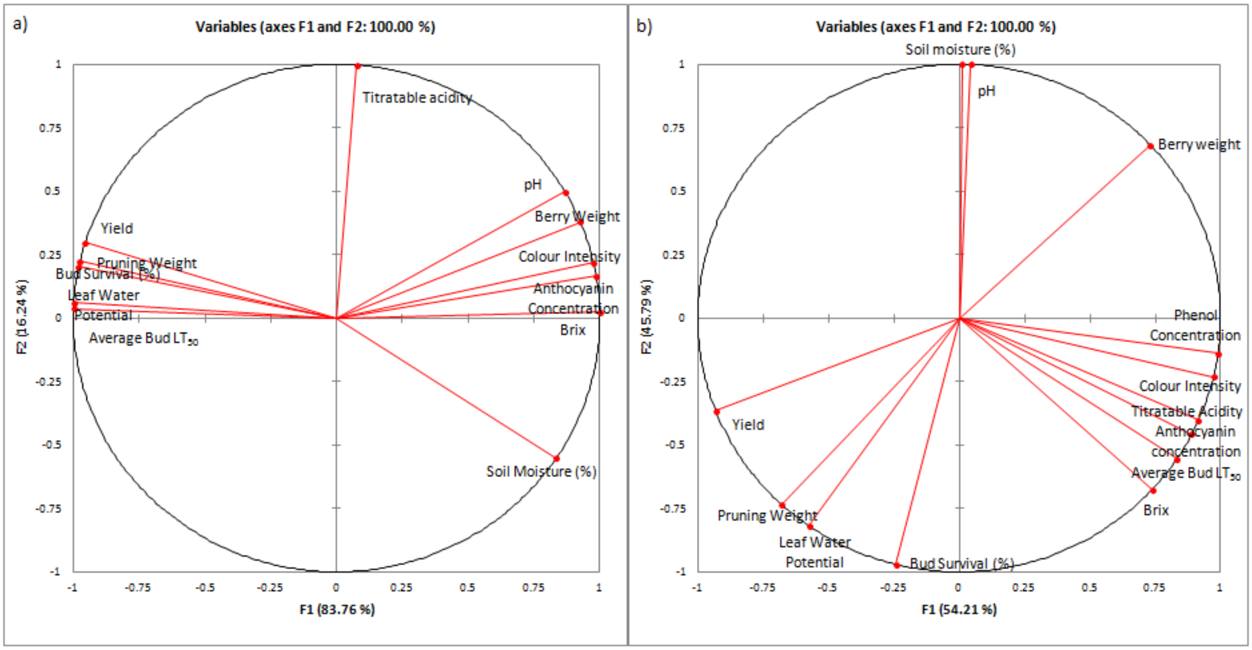

Figure 2.9 Principal component analysis diagrams of the Cave Spring Cabernet franc vineyard block for a) 2010 and b) 2011. Variables include berry composition, vine characteristics, and winter hardiness characteristics. PCA was run with three clusters and two factors. Phenol concentration relationships are not shown in a) since this variable was not analysed due to strong collinearity trends.

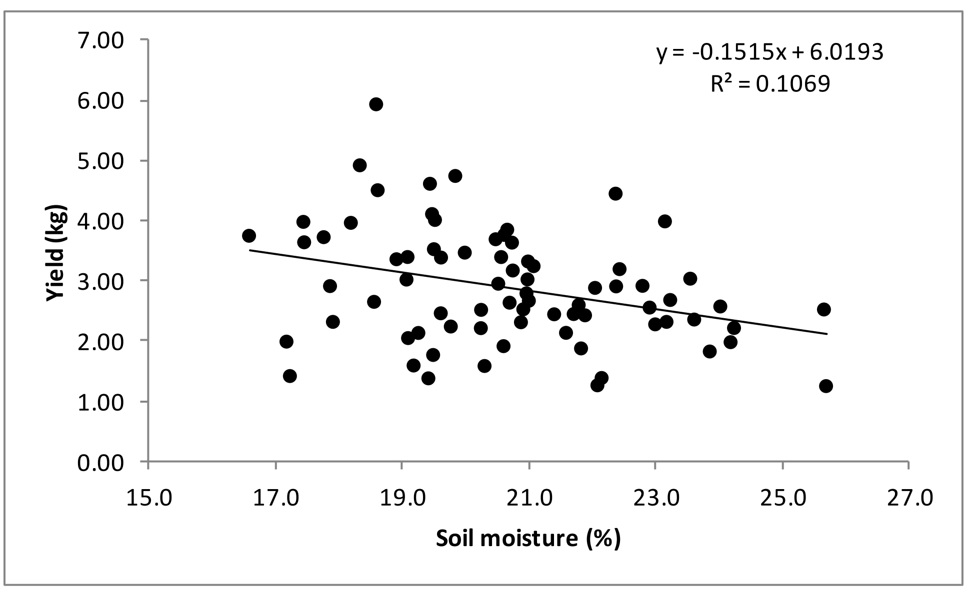

Figure 2.10 Yield vs. Soil moisture scatter-plot for the Cave Spring Cabernet franc block in 2010.

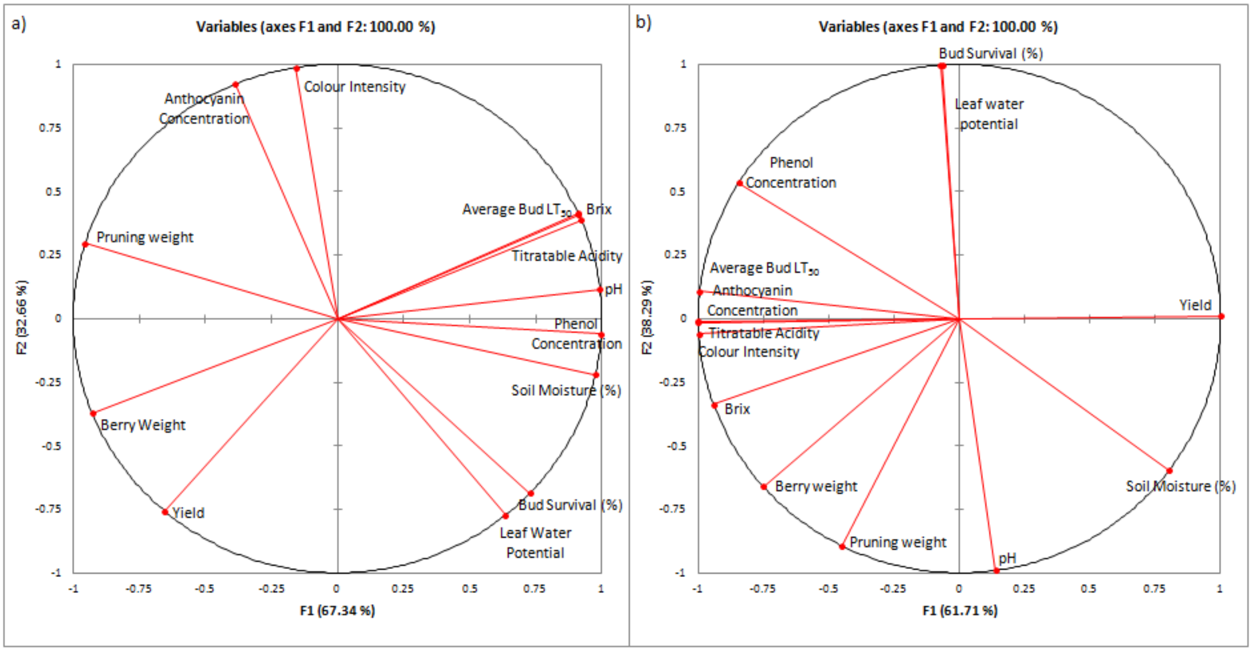

Figure 2.11 Principal component analysis diagrams of the Lowrey Cabernet franc vineyard block for a) 2010 and b) 2011. Variables include berry composition, vine characteristics, and winter hardiness characteristics. PCA was run with three clusters and two factors.

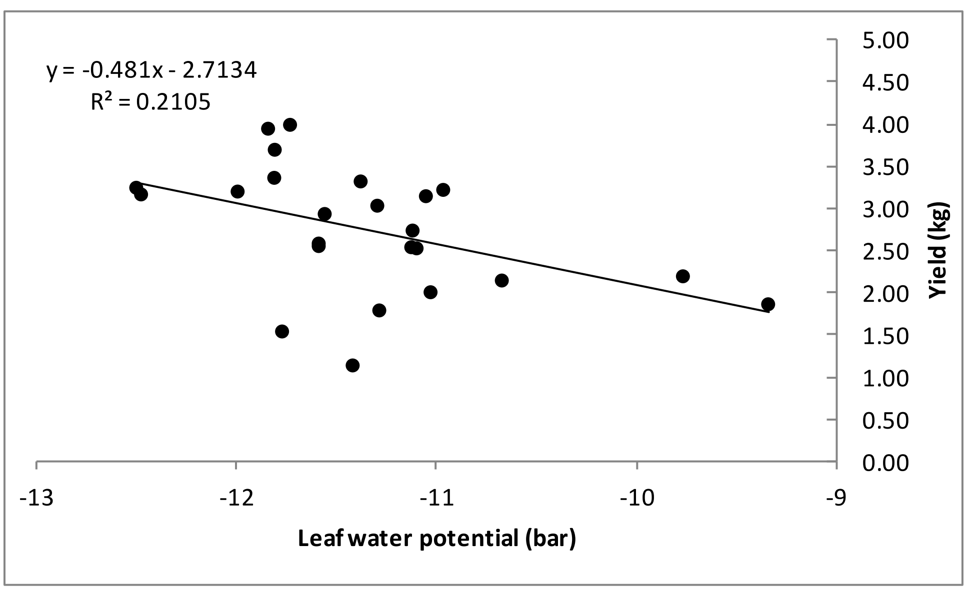

Figure 2.12 Yield vs. leaf water potential scatter-plot for the Lowrey Cabernet franc block in 2010.

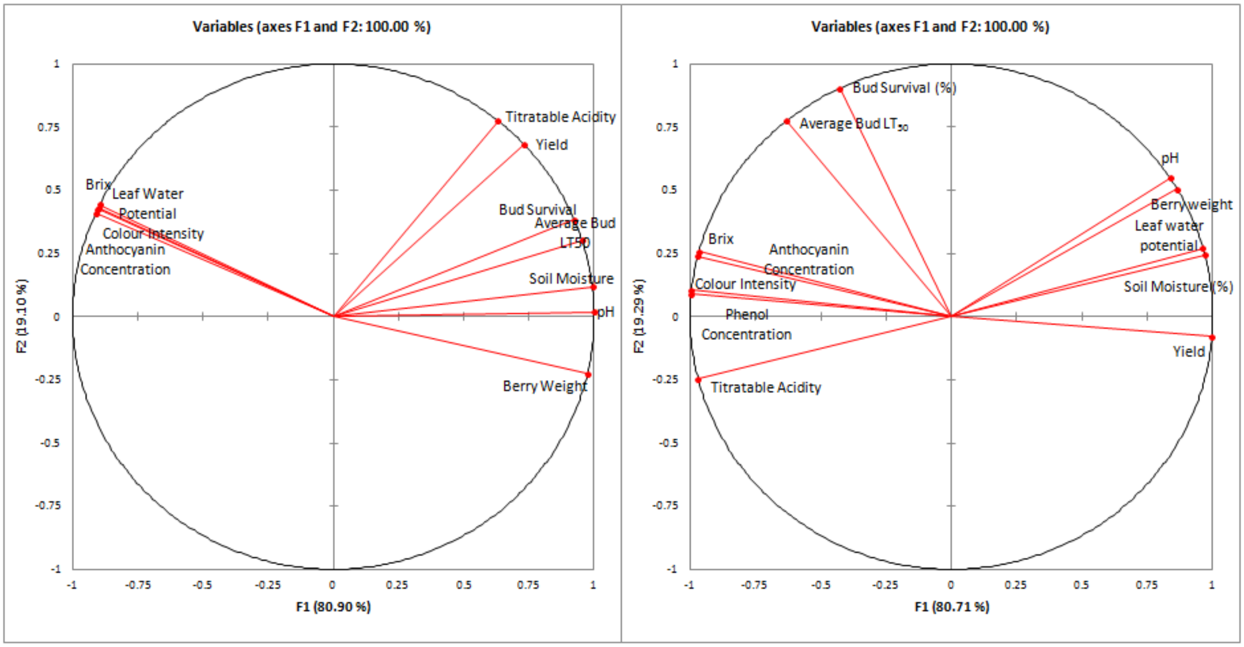

Figure 2.13 Principal component analysis diagrams of all Cabernet franc vineyard blocks for a) 2010 and b) 2011. Variables include berry composition, vine characteristics, and winter hardiness characteristics. PCA was run with three clusters and two factors. Phenol concentration relationships are not shown in a) since this variable was not analysed in the Cave Spring block due to strong collinearity trends.

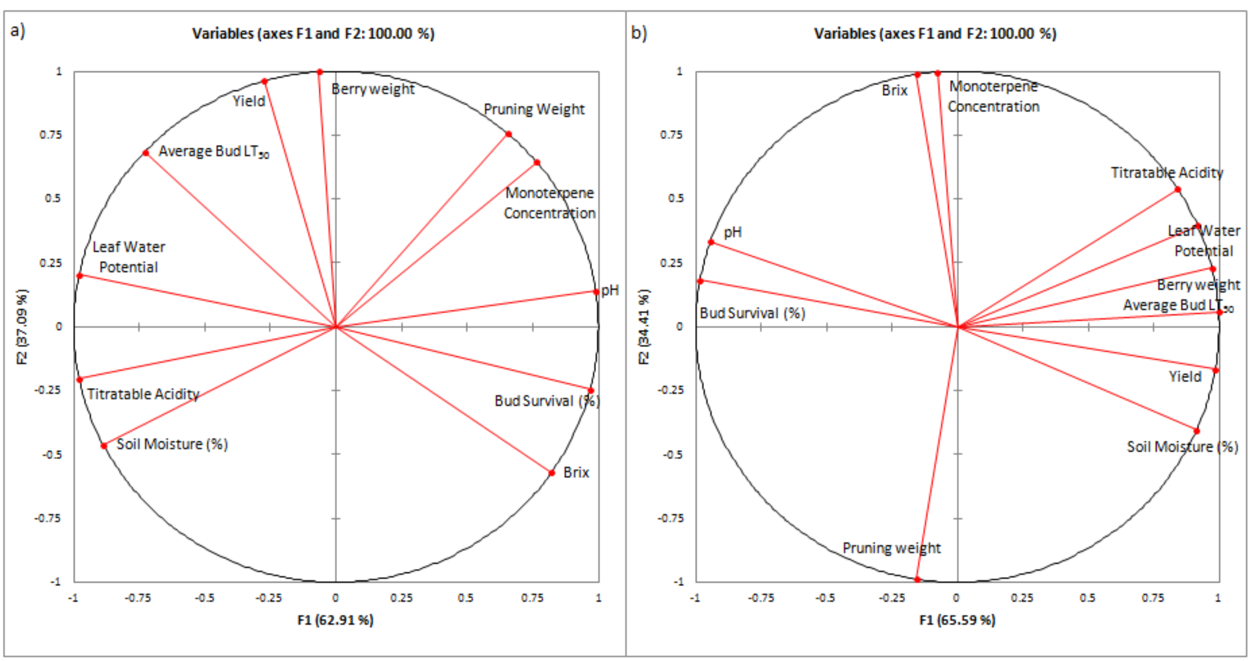

Figure 2.14 Principal component analysis diagrams of the Buis Riesling vineyard block for a) 2010 and b) 2011. Variables include berry composition, vine characteristics, and winter hardiness characteristics. PCA was run with three clusters and two factors.

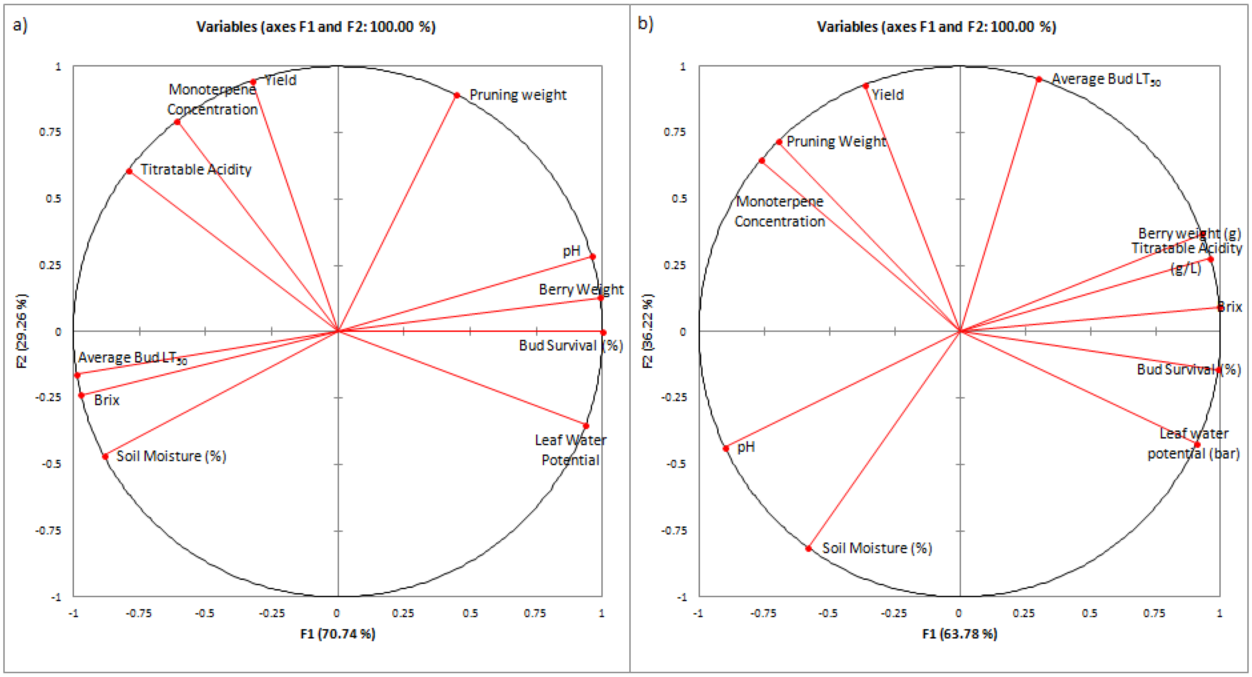

Figure 2.15 Principal component analysis diagrams of the George Riesling vineyard block for a) 2010 and b) 2011. Variables include berry composition, vine characteristics, and winter hardiness characteristics. PCA was run with three clusters and two factors.

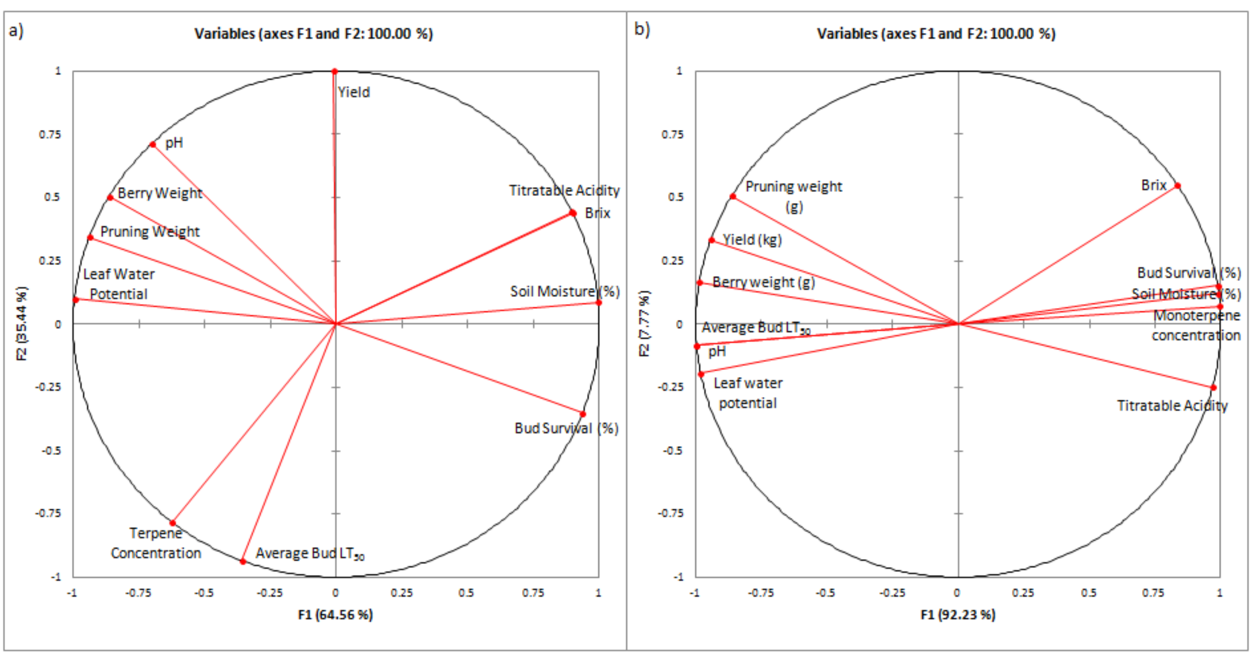

Figure 2.16 Principal component analysis diagrams of the Hughes Riesling vineyard block for a) 2010 and b) 2011. Variables include berry composition, vine characteristics, and winter hardiness characteristics. PCA was run with three clusters and two factors.

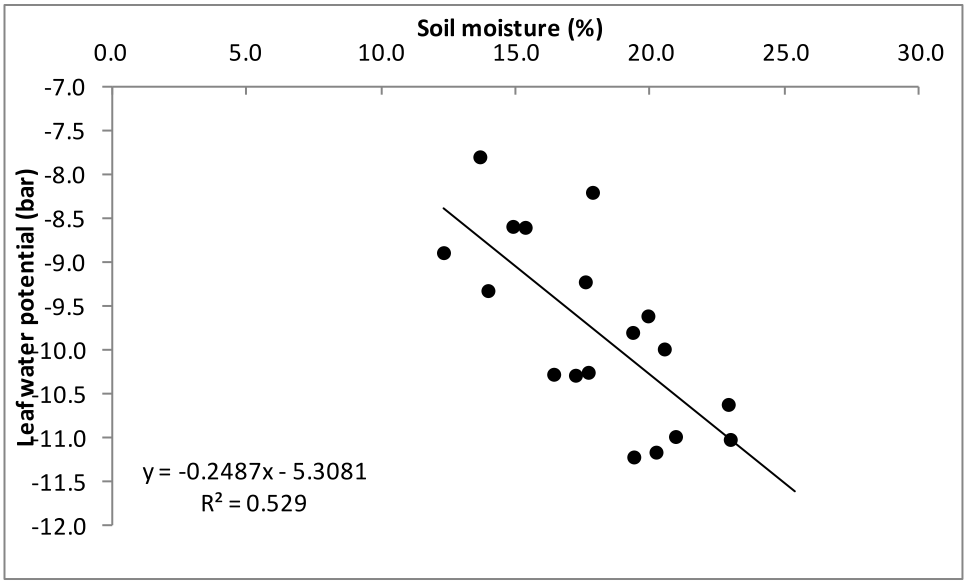

Figure 2.17 Leaf water potential vs. Soil moisture scatter-plot for the Hughes Riesling block in 2011.

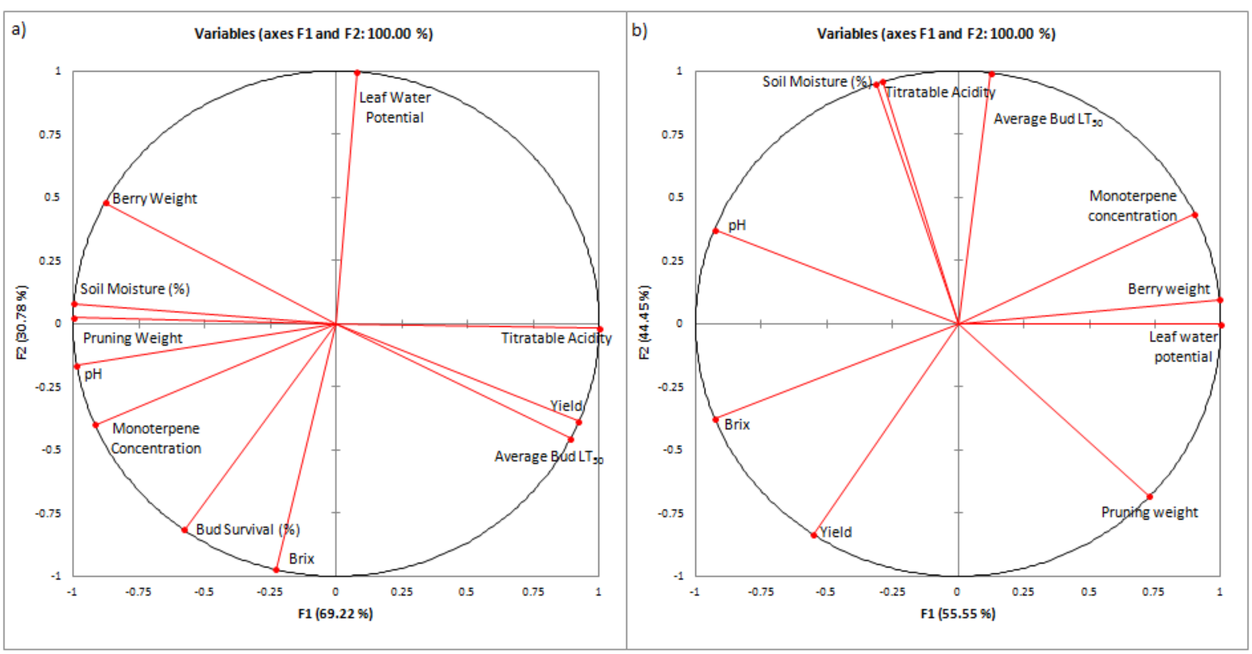

Figure 2.18 Principal component analysis diagrams of the Lambert Riesling vineyard block for a) 2010 and b) 2011. Variables include berry composition, vine characteristics, and winter hardiness characteristics. PCA was run with three clusters and two factors.

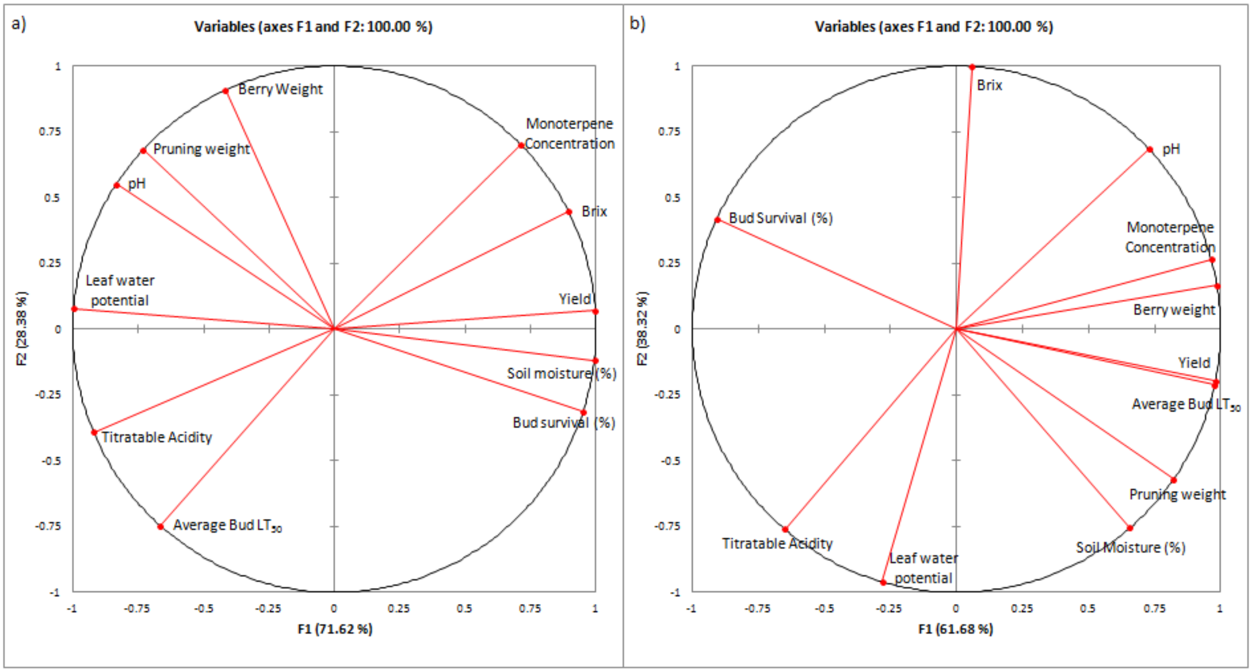

Figure 2.19 Principal component analysis diagrams of the Cave Spring Riesling vineyard block for a) 2010 and b) 2011. Variables include berry composition, vine characteristics, and winter hardiness characteristics. PCA was run with three clusters and two factors.

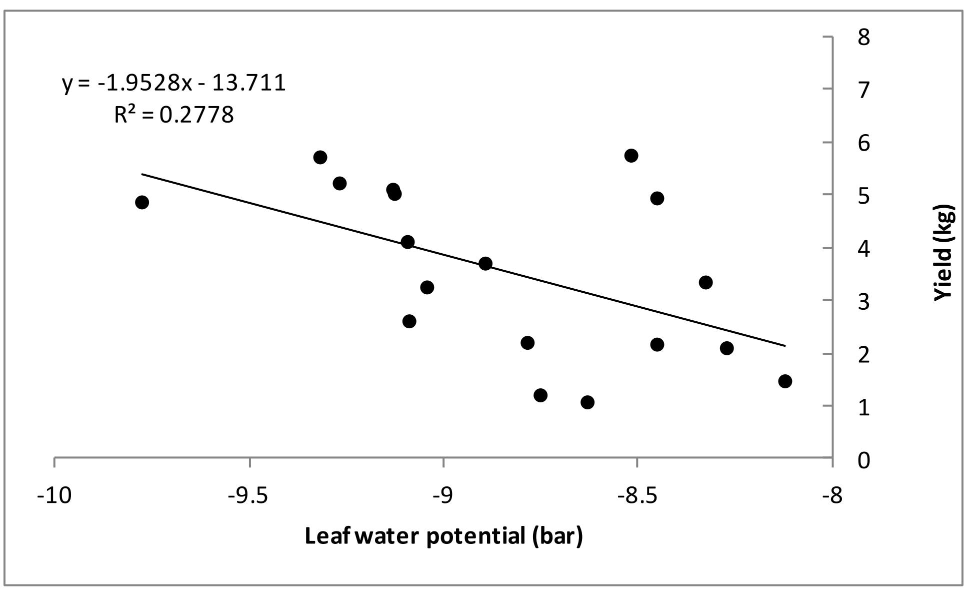

Figure 2.20 Yield vs. Leaf water potential scatter-plot for the Cave Spring Riesling block in 2010.

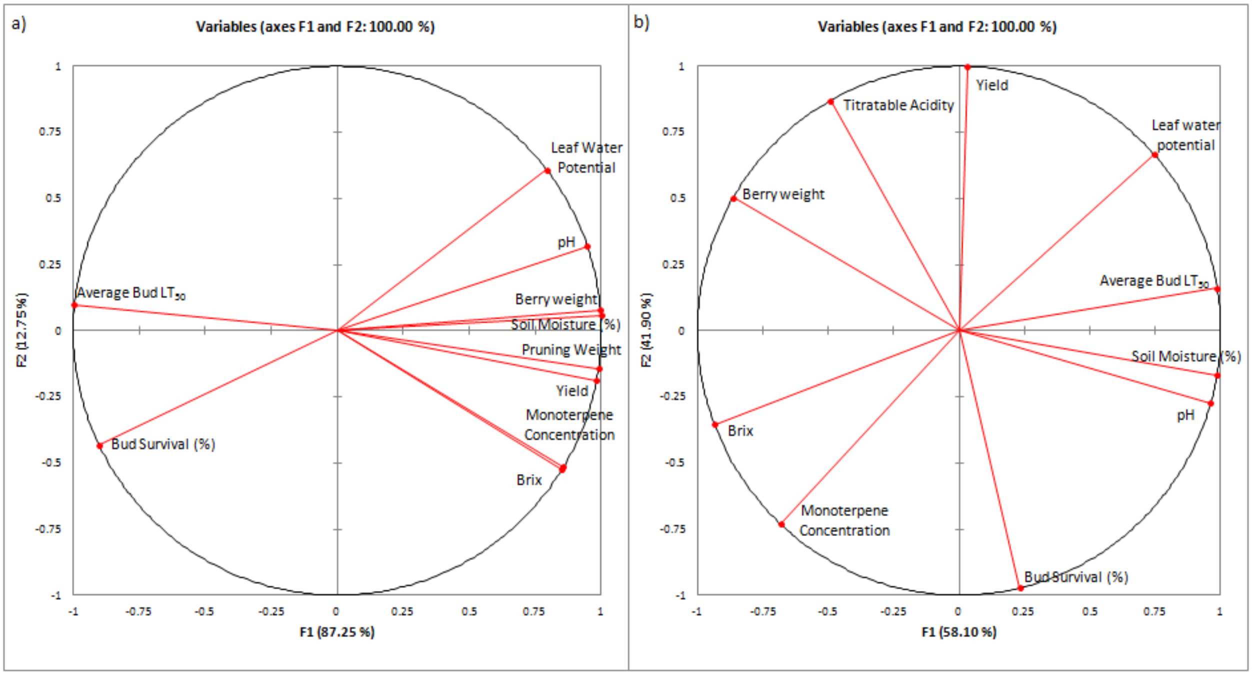

Figure 2.21 Principal component analysis diagrams of the Lowrey Riesling vineyard block for a) 2010 and b) 2011. Variables include berry composition, vine characteristics, and winter hardiness characteristics. PCA was run with three clusters and two factors.

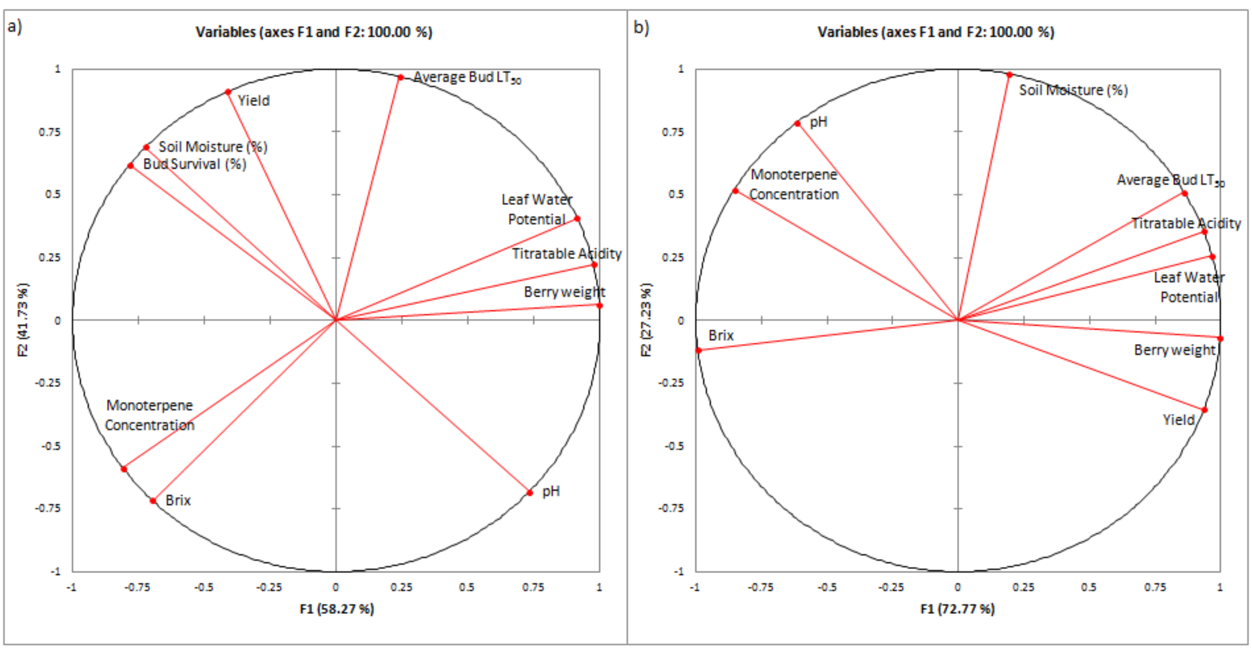

Figure 2.22 Principal component analysis diagrams of all the Riesling vineyard blocks for a) 2010 and b) 2011. Variables include berry composition, vine characteristics, and winter hardiness characteristics. PCA was run with three clusters and two factors.

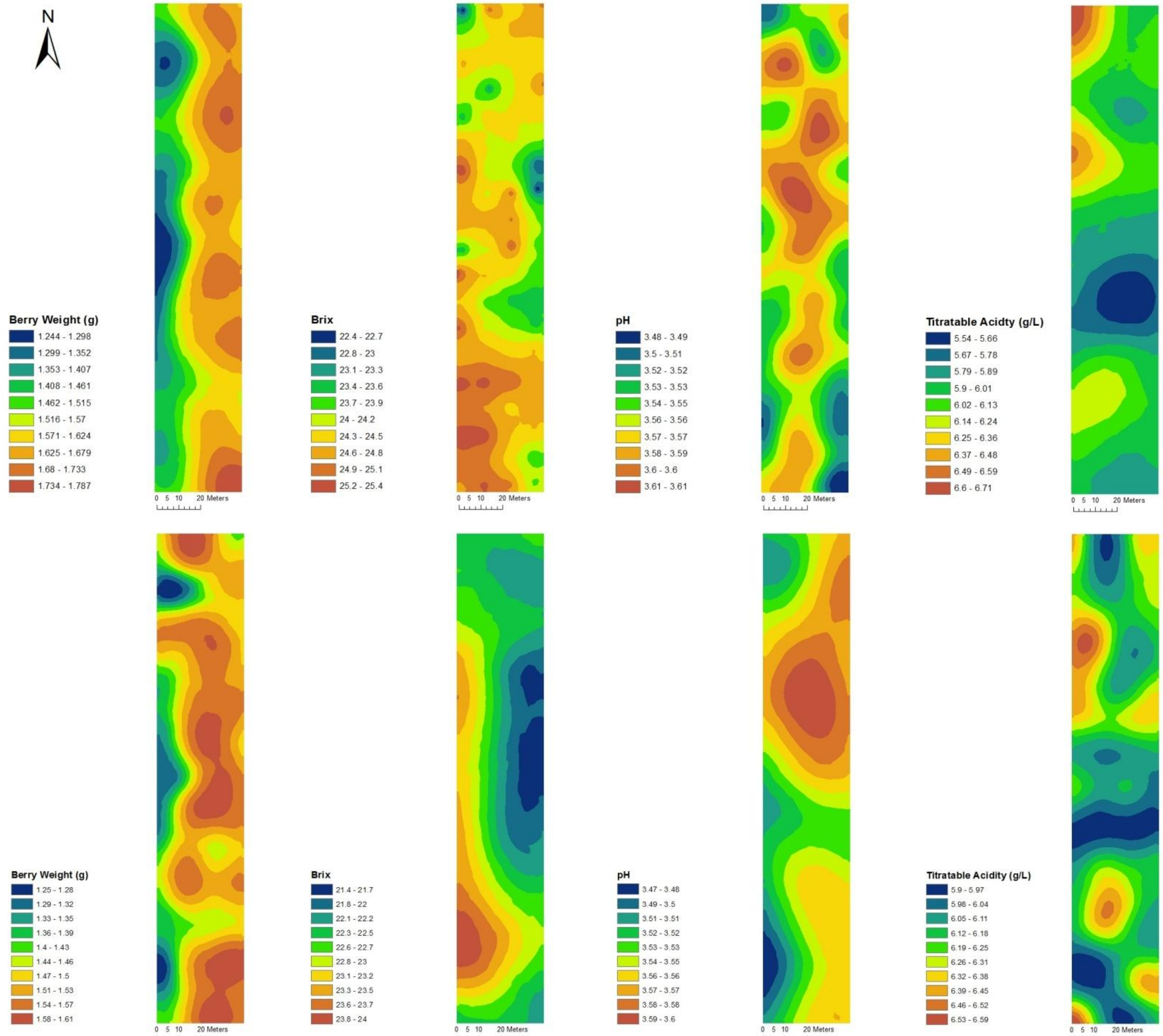

Figure 2.23 Maps of berry weight, Brix, pH, and titratable acidity for the Buis Cabernet franc block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

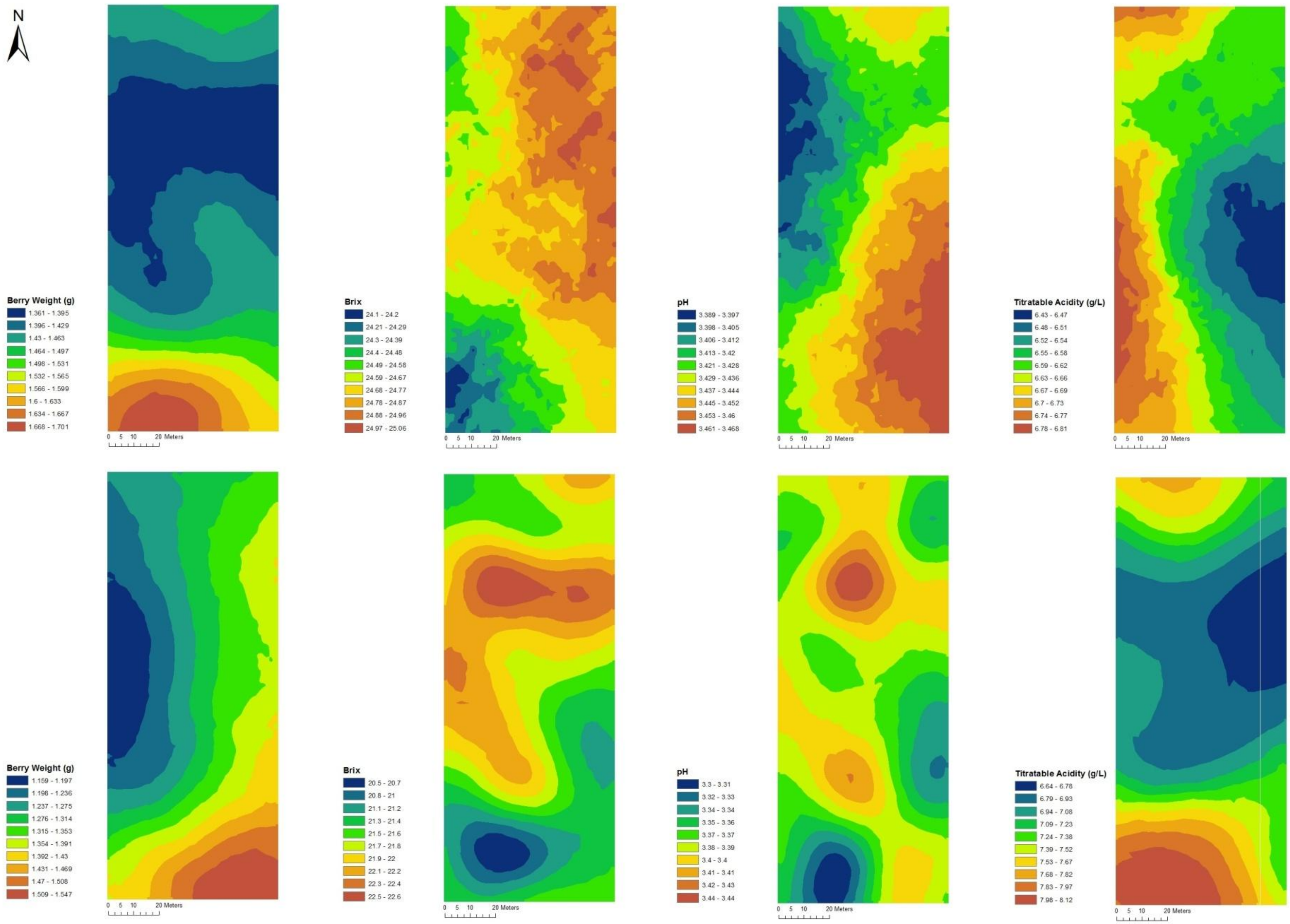

Figure 2.24 Maps of berry weight, Brix, pH, and titratable acidity for the George Cabernet franc block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

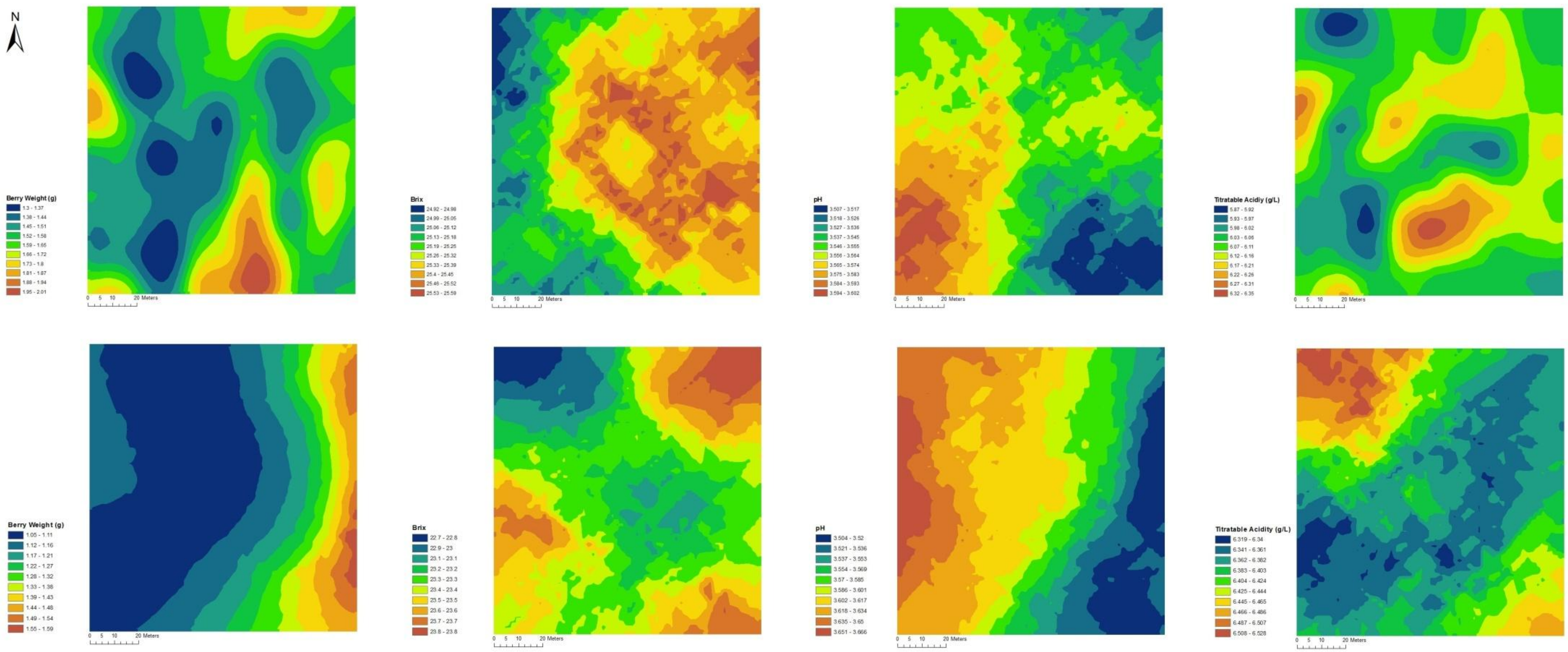

Figure 2.25 Maps of berry weight, Brix, pH, and titratable acidity for the Kocsis Cabernet franc block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

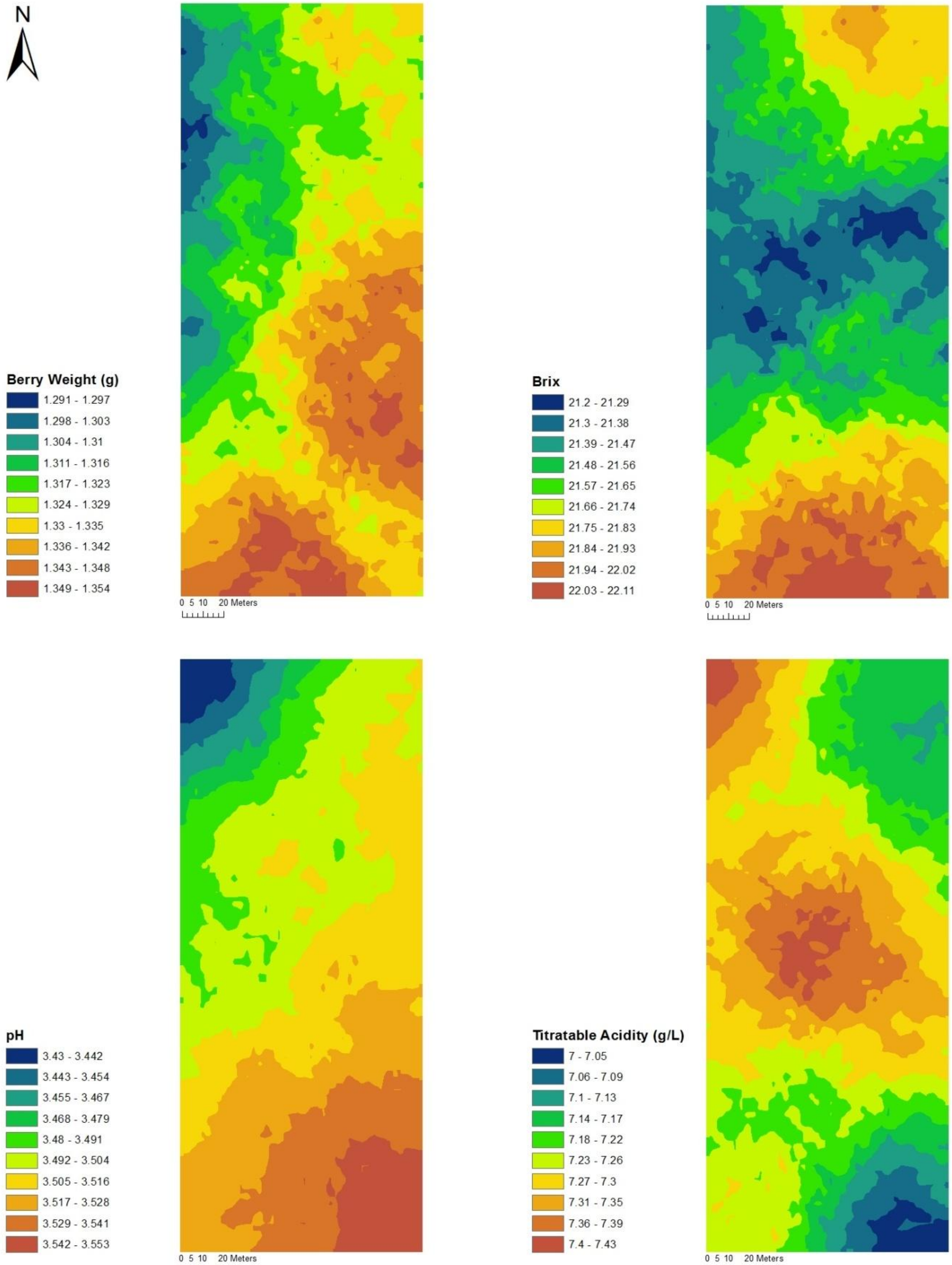

Figure 2.26 Maps of berry weight, Brix, pH, and titratable acidity for the Lambert Cabernet franc block in 2011.

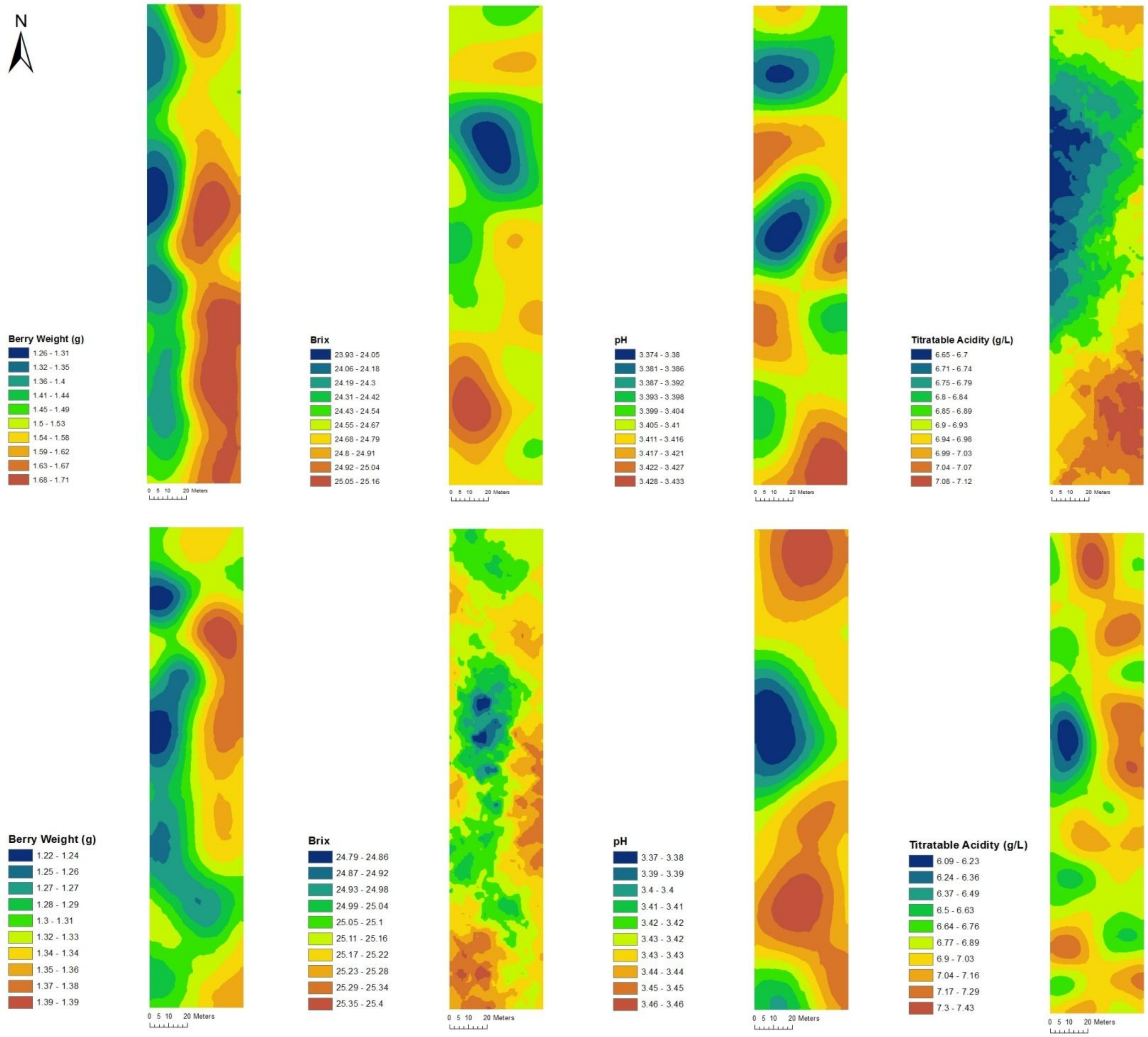

Figure 2.27 Maps of berry weight, Brix, pH, and titratable acidity for the Cave Spring Cabernet franc block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

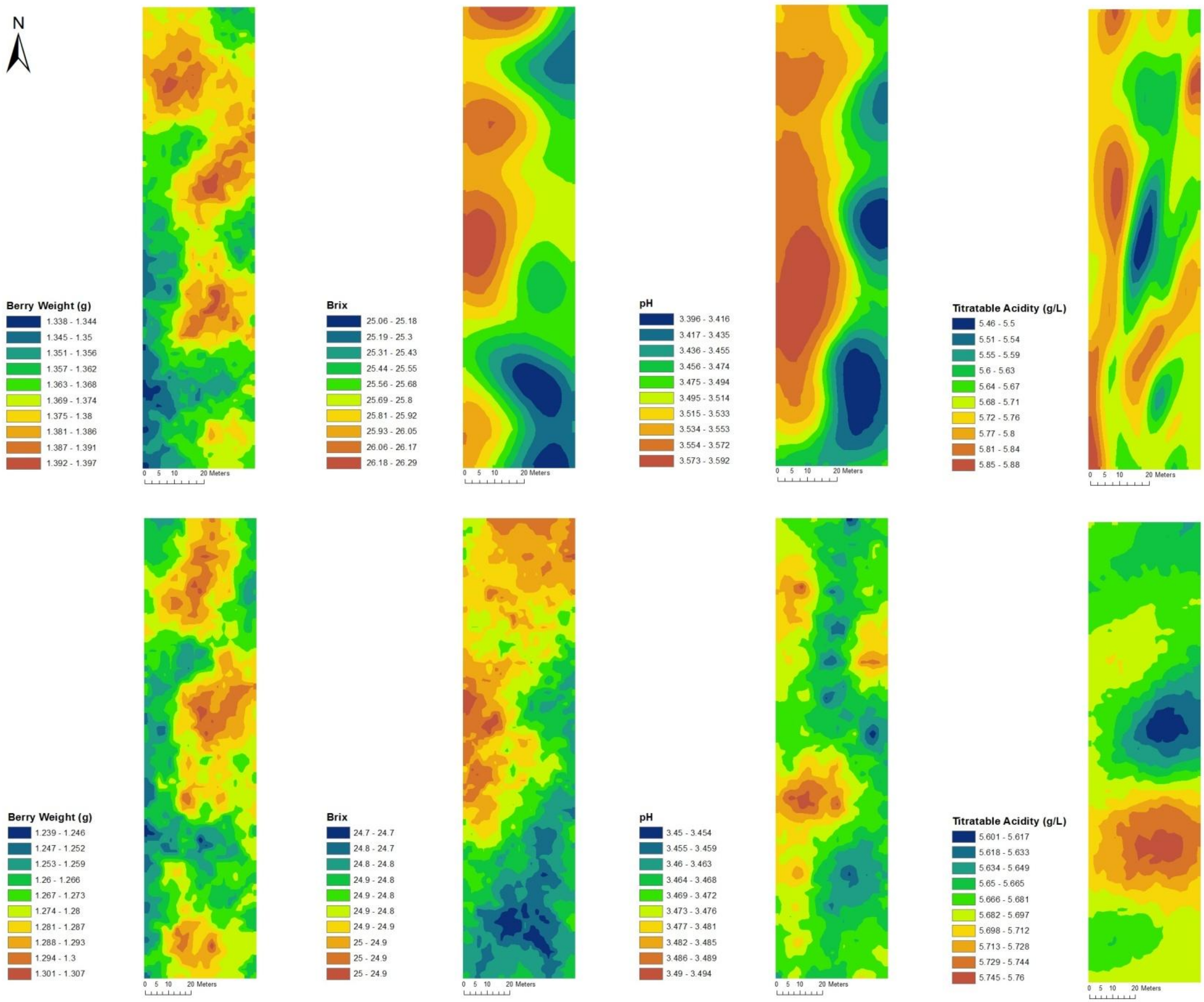

Figure 2.28 Maps of berry weight, Brix, pH, and titratable acidity for the Lowrey Cabernet franc block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

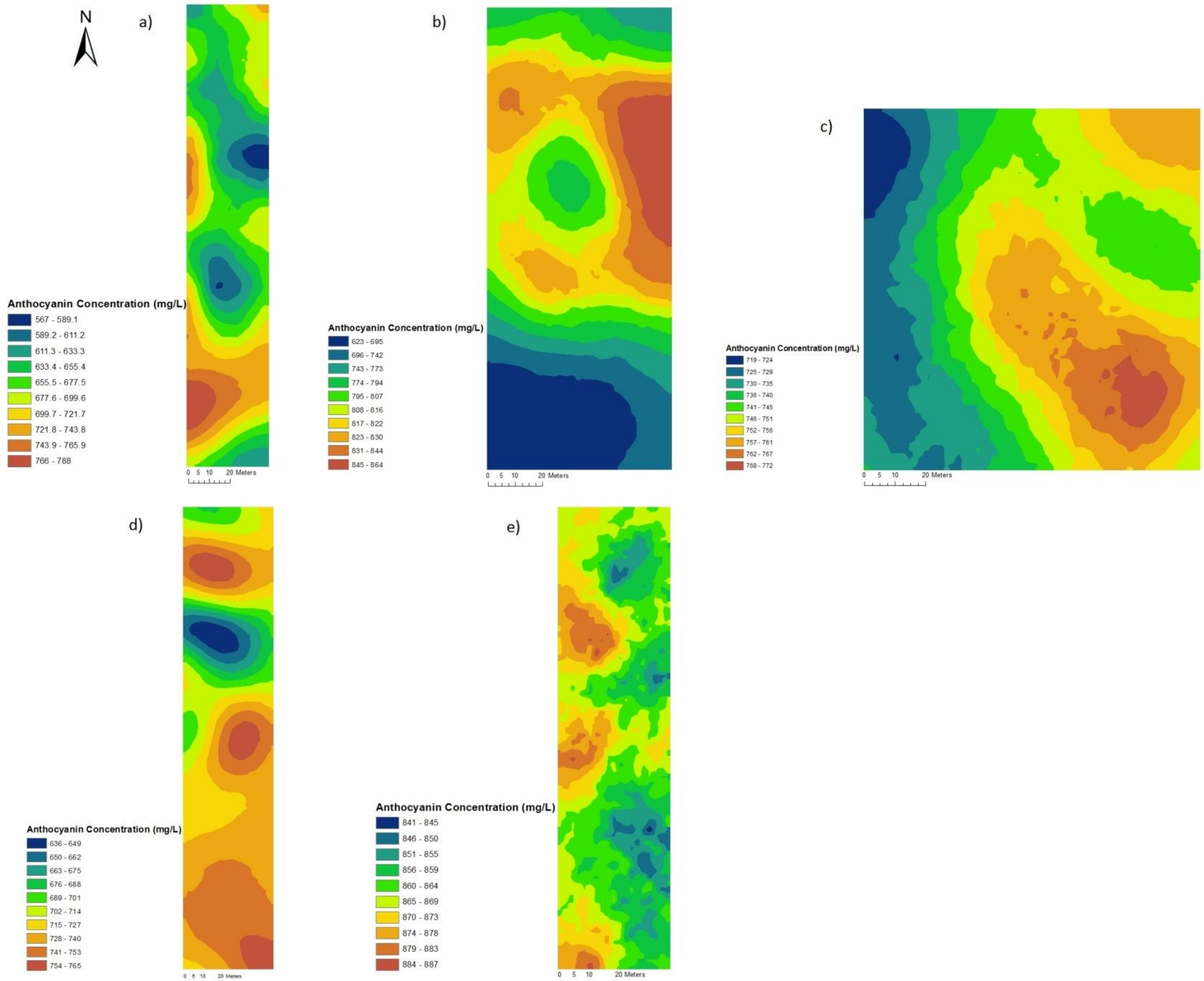

Figure 2.29 Maps of anthocyanin concentrations in 2010. a) Buis, b) George, c) Kocsis, d) Cave Spring, e) Lowrey.

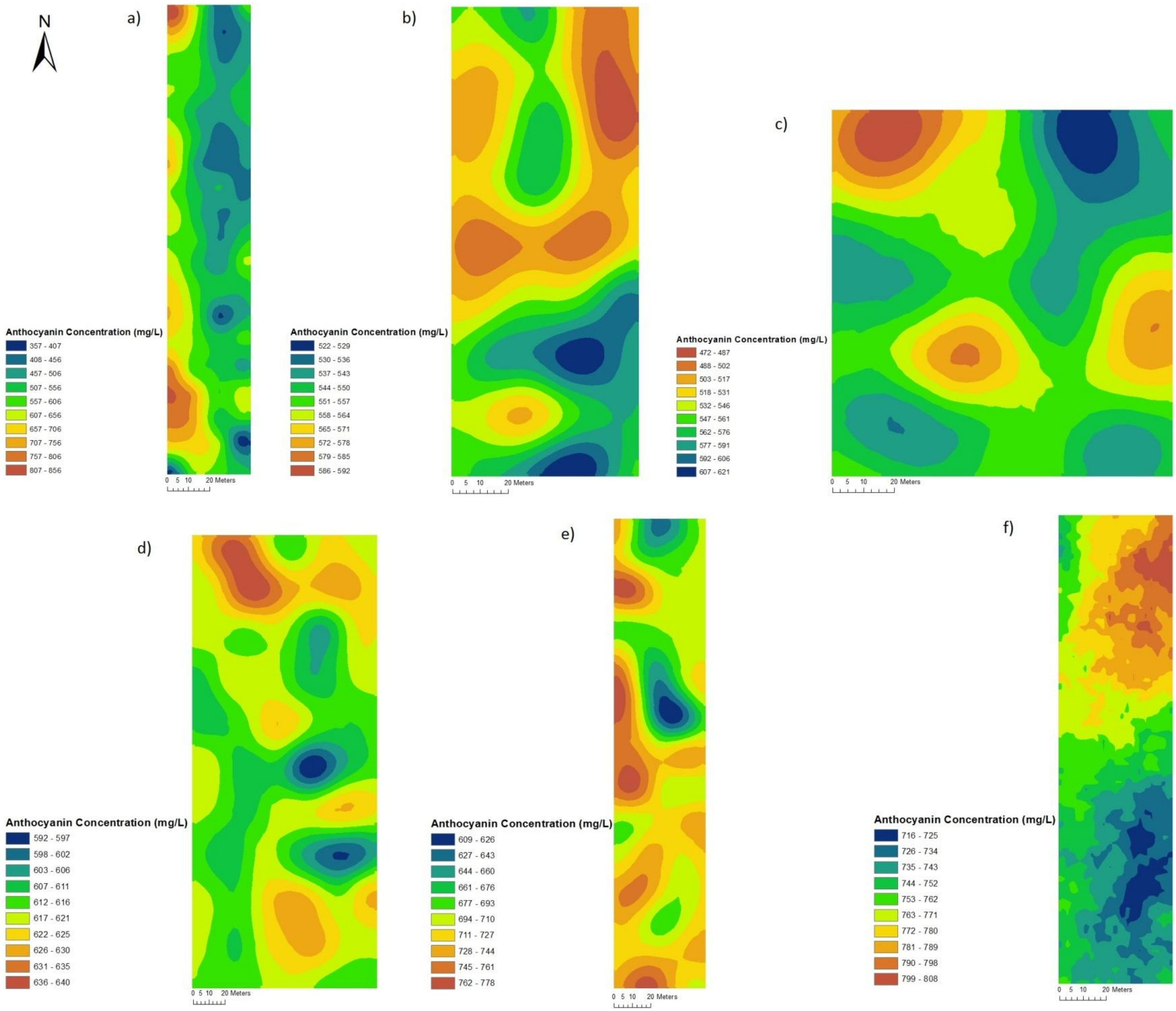

Figure 2.30 Maps of anthocyanin concentrations in 2011. a) Buis, b) George, c) Kocsis, d) Lambert, e) Cave Spring, f) Lowrey.

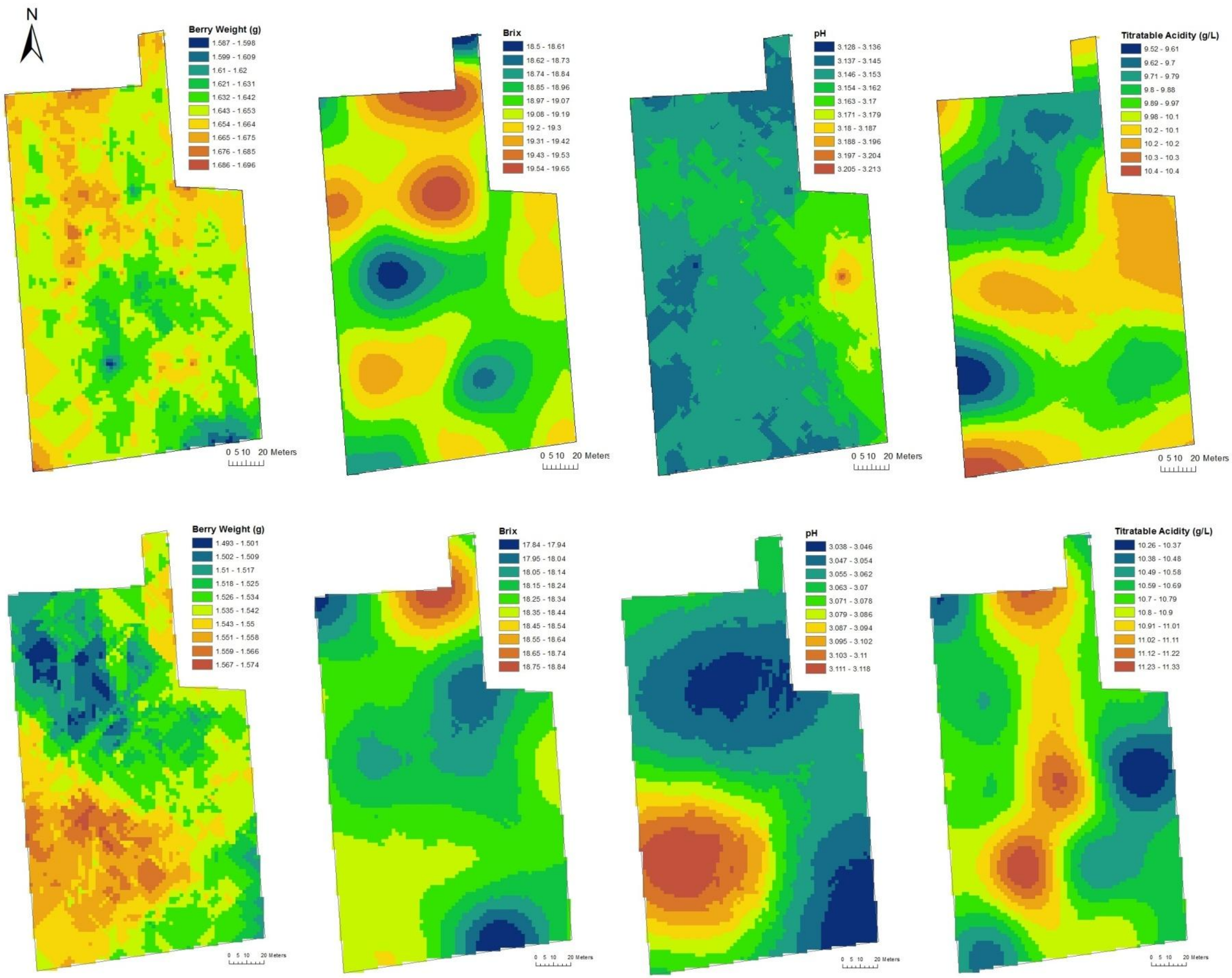

Figure 2.31 Maps of berry weight, Brix, pH, and titratable acidity for the Buis Riesling block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

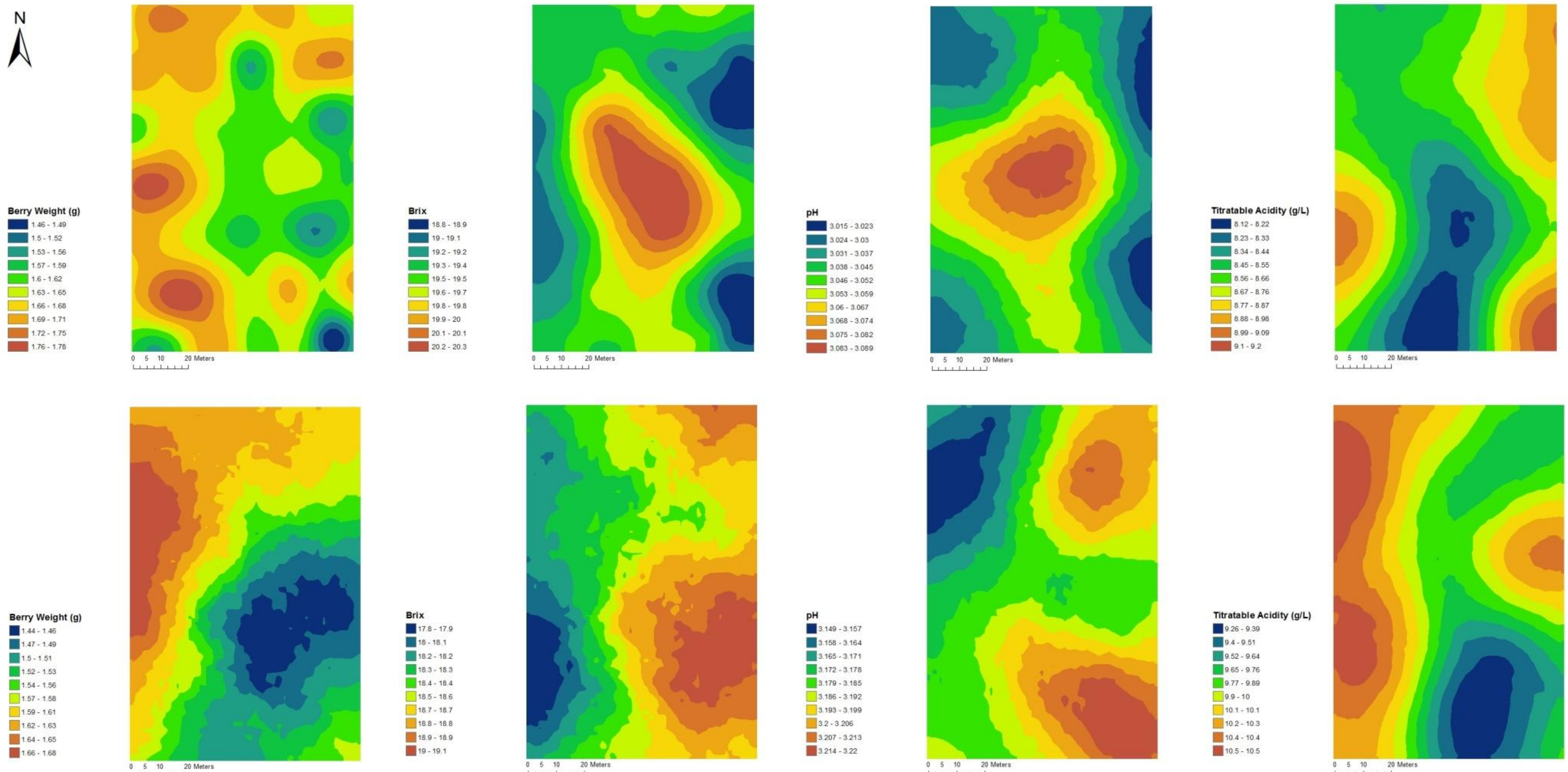

Figure 2.32 Maps of berry weight, Brix, pH, and titratable acidity for the George Riesling block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

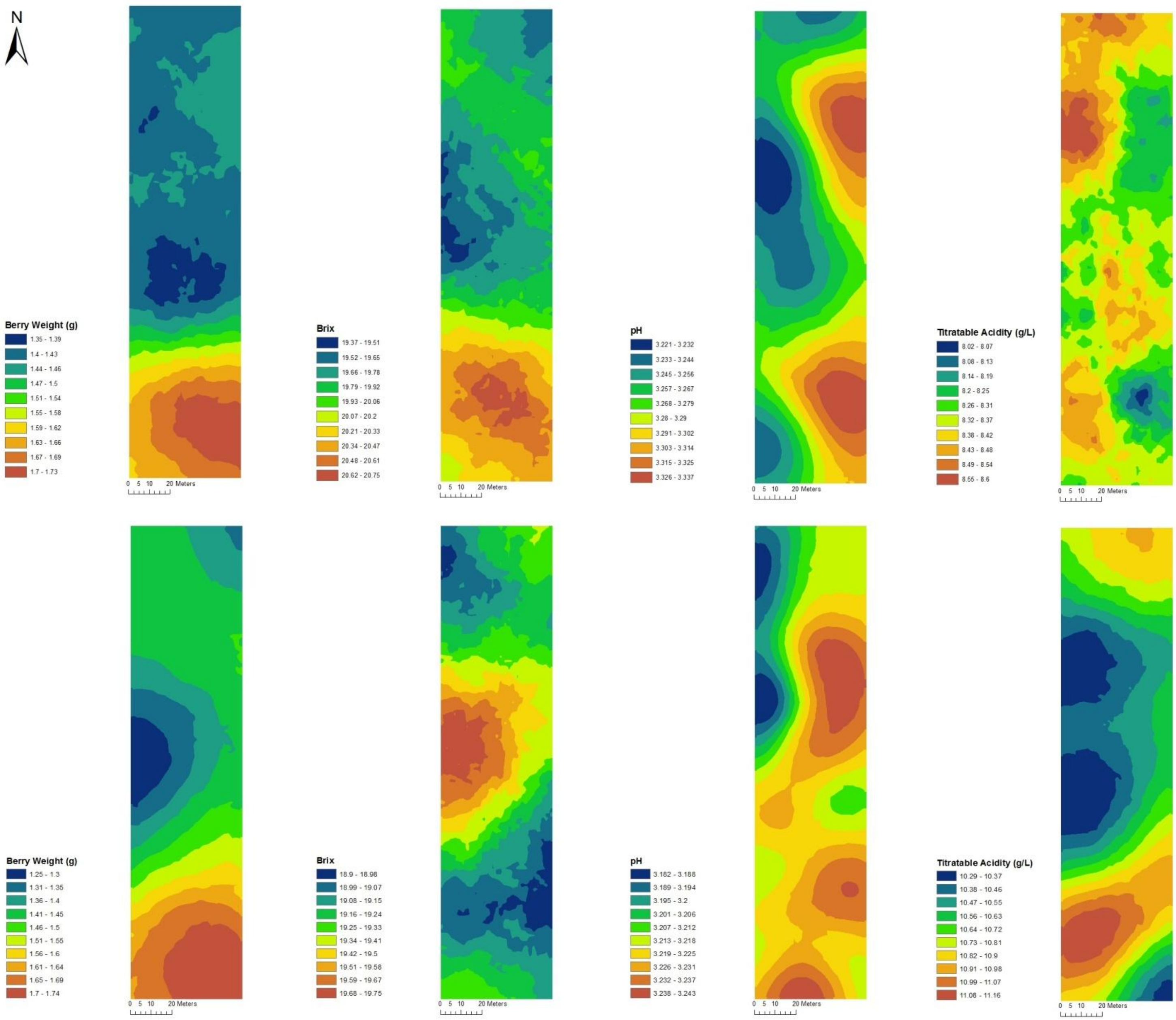

Figure 2.33 Maps of berry weight, Brix, pH, and titratable acidity for the Hughes Riesling block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

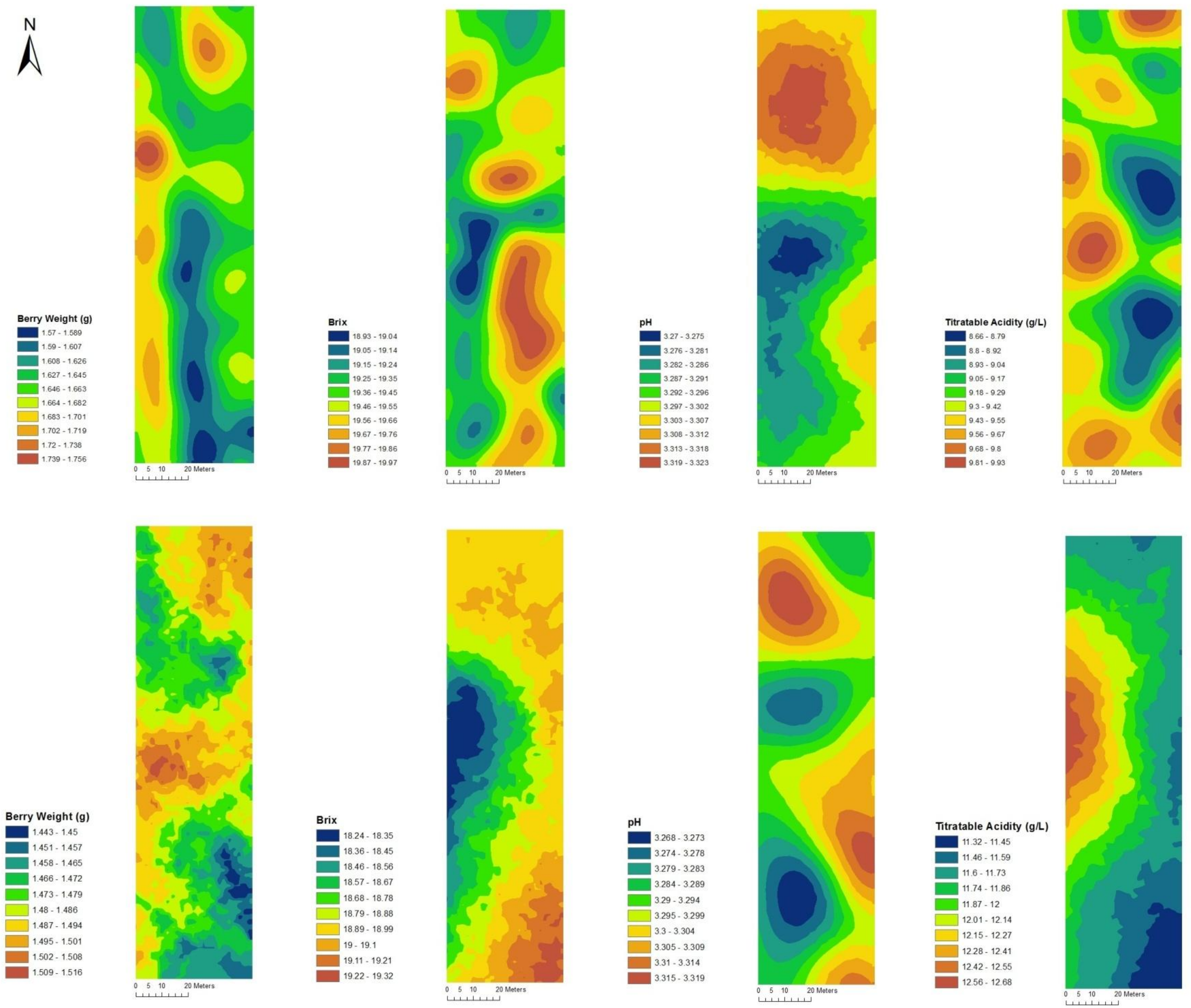

Figure 2.34 Maps of berry weight, Brix, pH, and titratable acidity for the Lambert Riesling block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

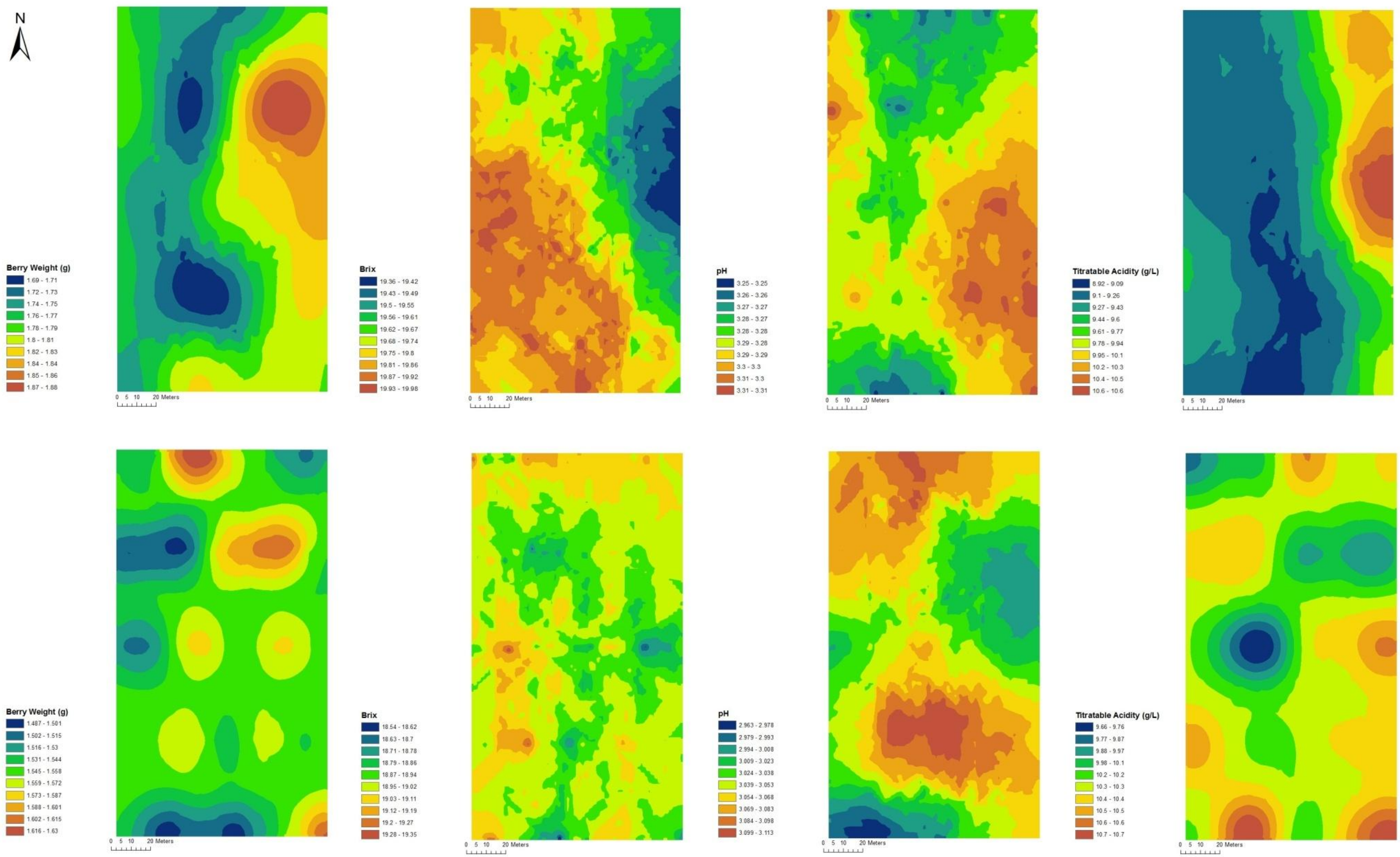

Figure 2.35 Maps of berry weight, Brix, pH, and titratable acidity for the Cave Spring Riesling block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

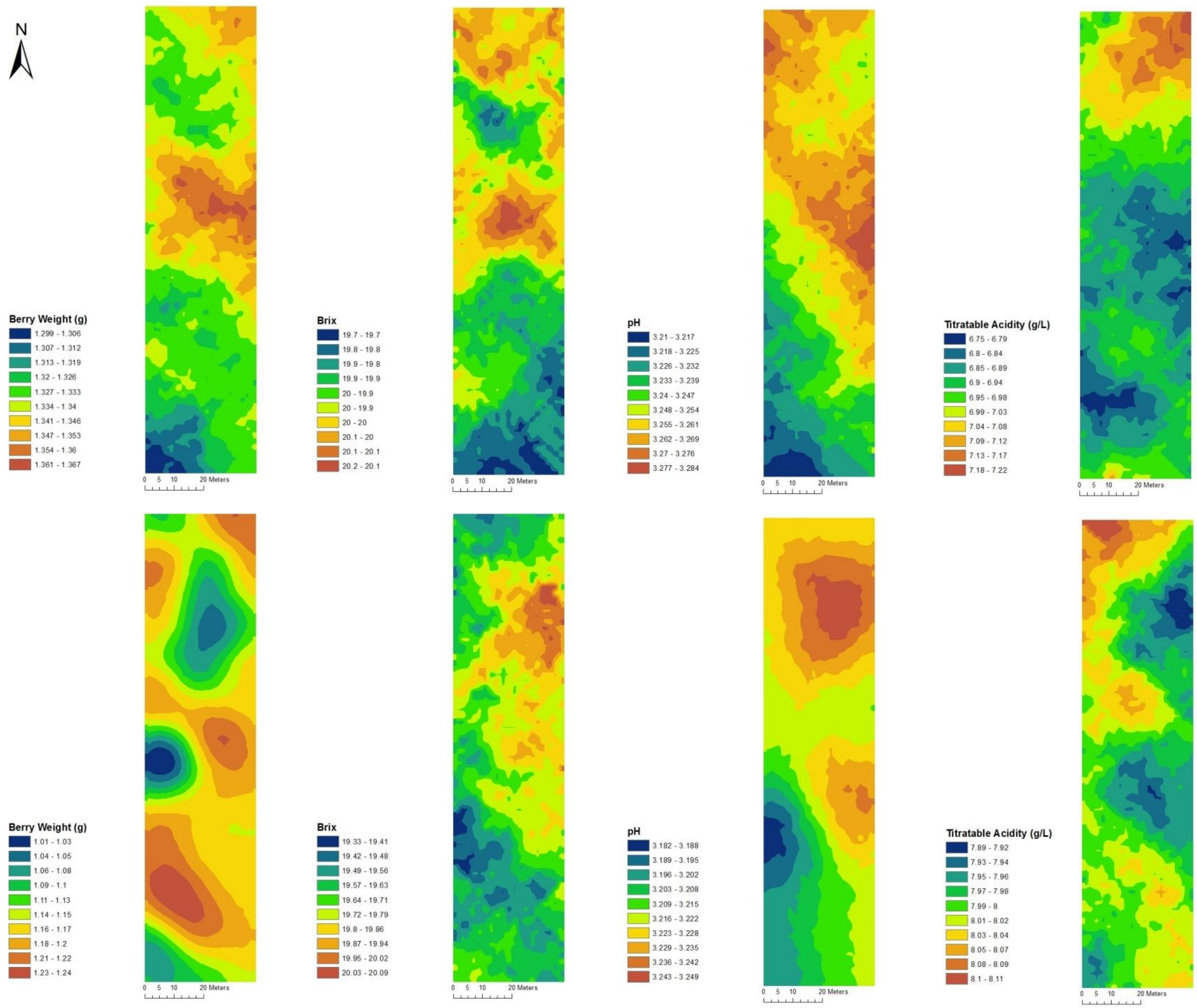

Figure 2.36 Maps of berry weight, Brix, pH, and titratable acidity for the Lowrey Riesling block in both 2010 and 2011. Top: 2010 berry weight, Brix, pH, and TA. Bottom: 2011 berry weight, Brix, pH, and TA.

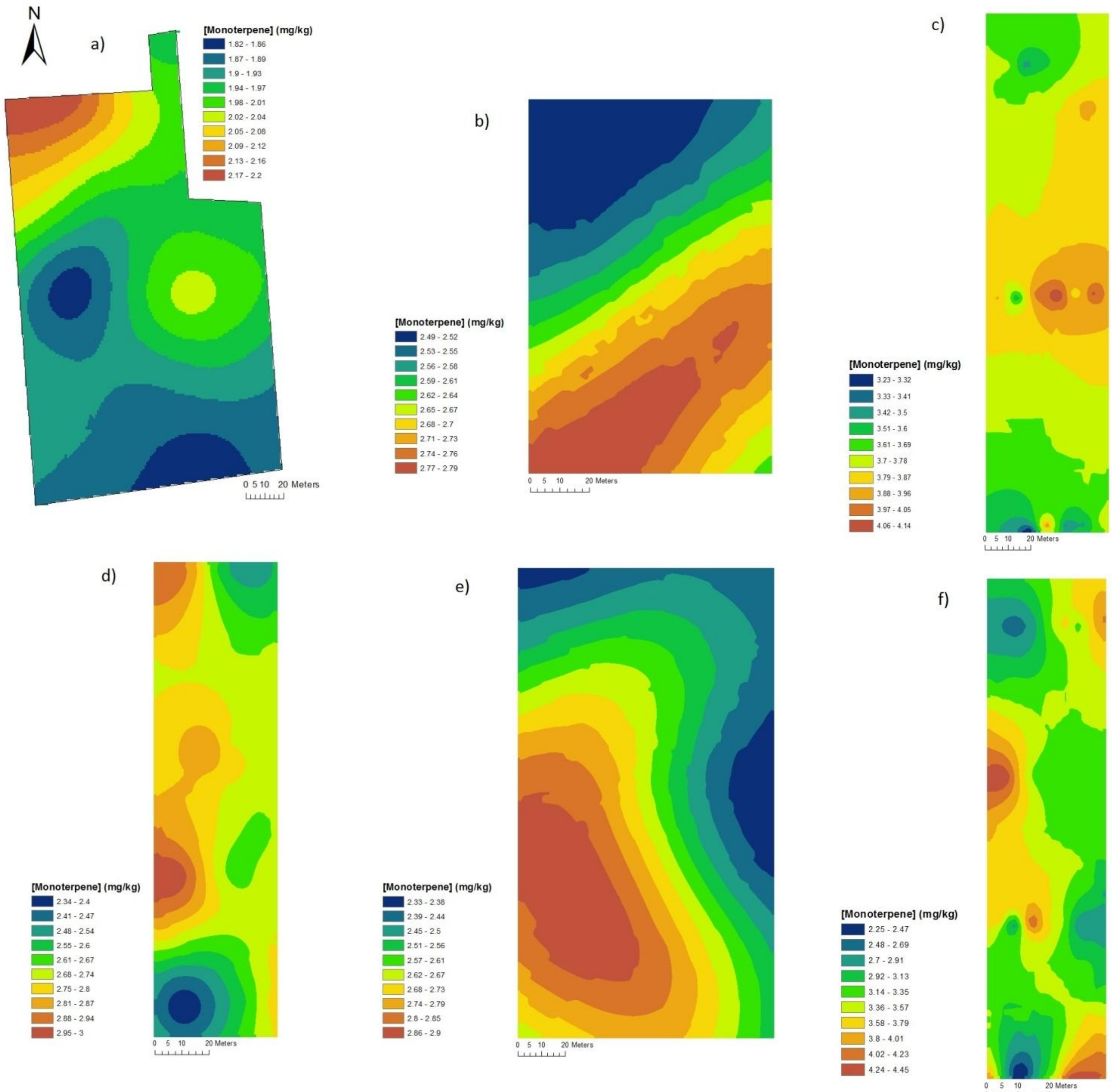

Figure 2.37 Maps of monoterpene concentrations in 2010. a) Buis, b) George, c) Hughes, d) Lambert, e) Cave Spring, f) Lowrey.

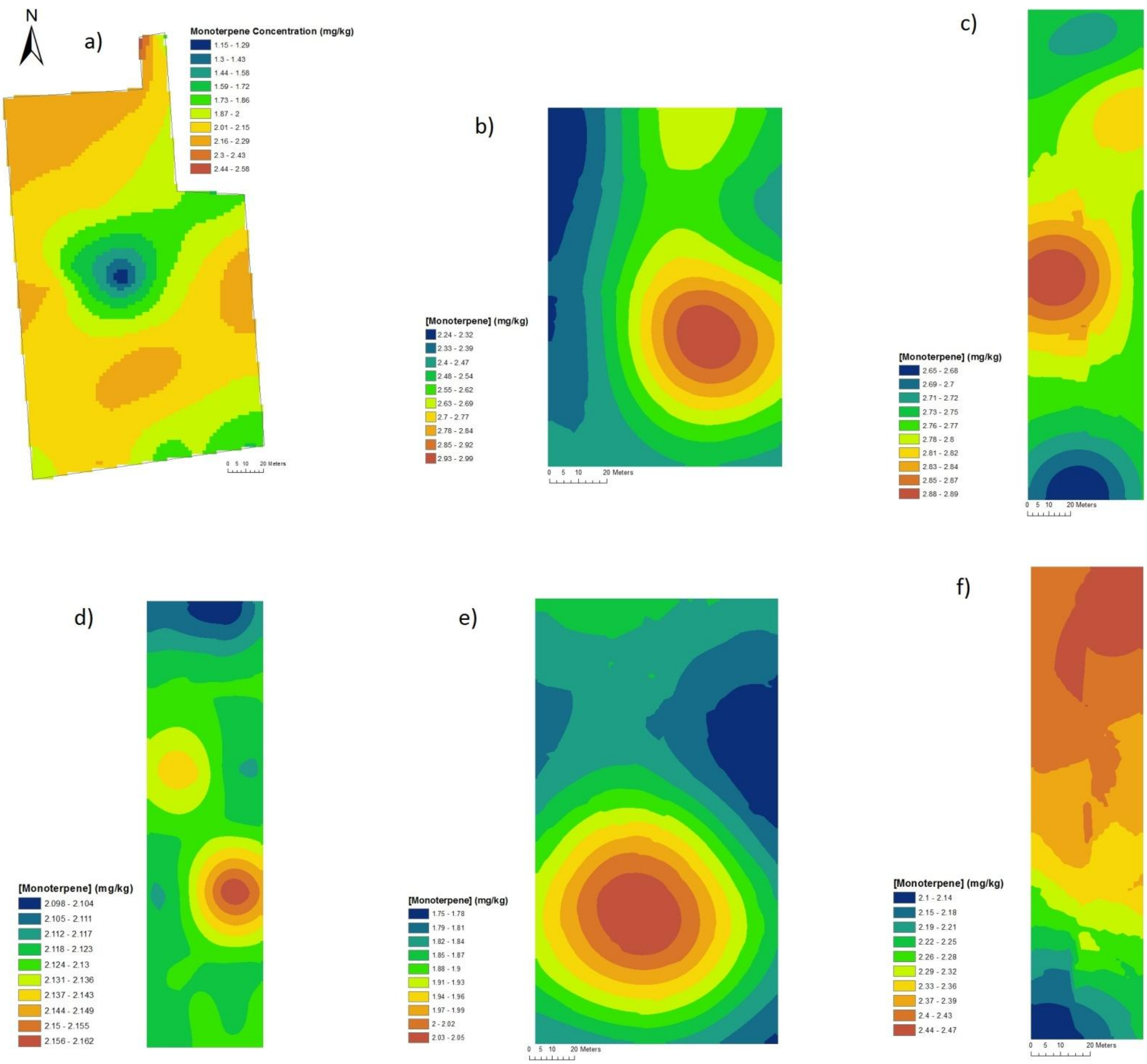

Figure 2.38 Maps of monoterpene concentrations in 2011. a) Buis, b) George, c) Hughes, d) Lambert, e) Cave Spring, f) Lowrey.

Chapter 3: The Temporal Patterns of Yield, Water Metrics, Winter Hardiness, and Bud Survival

3.1 Introduction

The concept of *terroir* is based on the idea that a vineyard's location affects the grapevines and their resulting fruit (Reynolds et al. 2007, Schlosser et al. 2005). One of the many practices to stem from this concept is precision viticulture which promotes the use of management zones within established vineyards in order to control the growth and production of grapevines (Bramley and Hamilton 2004, Bramley et al. 2011). Through the use of spatial analysis, precision viticulture recognises that a plot of land does not have homogenous characteristics, but instead varies throughout (Bramley and Hamilton 2004). These patterns of variation define the management zones – regions within a vineyard block which are expected to display uniform temporal characteristics (Morari et al. 2009).

Precision viticulture relies heavily on the assumption that patterns within a vineyard are temporally stable (Bramley and Hamilton 2004). However, this assumption may sometimes prove false. For instance, although Bramley and Hamilton (2004) found that most of their study sites were consistent from year to year, their Merlot site in Clare Valley (South Australia) showed inconsistent yield patterns from 2000 to 2003. Similar results concerning yield were found by Reynolds et al. (2007) who studied Riesling in Ontario, Canada. Regardless, many studies have shown that spatial patterns of important vineyard characteristics are stable. For instance, studies in Australia and New Zealand have found that yield, vine size, and berry composition variables have similar spatial patterns from year to year (Bramley 2005, Bramley and Hamilton 2004, Bramley et al. 2011). Reynolds et al. (2007) reported that, although yield was not temporally stable, vine size patterns were. Additional work on Riesling vineyards by this research group has also shown stable spatial patterns regarding leaf ψ, soil moisture, and berry weight (Reynolds et al. 2010a, Reynolds et al. 2010b). Even studies outside of viticulture have shown that soil moisture spatial variation is temporally stable over long periods of time (Vinnikov et al. 1996).

Each of the studies mentioned above make use of GIS software and spatial interpolation processes. There are two main types of interpolation methods: deterministic interpolation (inverse distance weighting, IDW) and geostatistical interpolation (kriging; Erdogan 2009). At the root of both methods is Tobler's First Law which states that points closer in proximity to each other are more similar than points further away (Miller 2004). The use of this law and the accuracy of these interpolation methods allow for values at unsampled locations to be estimated, making spatial investigations of large areas (such as whole vineyards) possible.

Although many variables have been investigated for stable temporal patterns, winter bud hardiness has not been one of them. As with other vine characteristics, bud hardiness is affected by the location and environmental conditions of a vineyard. Bud hardiness responds quickly to fluctuations throughout the winter season, with bud LT_{50} measurements being strongly affected by ambient temperatures (Ferguson et al. 2011, Wolf and Cook 1992, Zabadal et al. 2007). However, a general pattern does emerge, with maximum winter hardiness being achieved by mid-winter and maintained until March (Basinger and Hellman 2006, Keller 2010, Wolf and Cook 1992, Zabadal et al. 2007).

Grapevine winter bud hardiness has been studied for decades, with Edgerton and Shaulis (1953) being among the first to evaluate bud survival based on the browning of bud tissue. Freezing tests have also been developed that allow for the measurement of hardiness within the laboratory (Clore et al. 1974, Edgerton and Shaulis 1953, Fennell 2004, Hamman et al. 1996, Howell et al. 1978, Howell and Shaulis 1980, Mills et al. 2006, Wolf and Cook 1994, Wolpert and Howell 1984). Two of the most popular freezing tests are thermal analysis and differential thermal analysis (DTA), both of which record the presence of high temperature exotherms (HTE, caused by extracellular ice) and low temperature exotherms (LTE, caused by intracellular ice; Badulescu and Ernst 2006, Burke et al. 1976, Fennell 2004, Zabadal et al. 2007). Regardless of the method used, results show that grapevine buds die between -11 ^{o}C to -24 ^{o}C in cool climate regions (Badulescu and Ernst 2006, Mills et al. 2006, Wolf and Cook 1994).

Once temperatures fall below these critical values, bud death and winter injury can occur. This can be a concern in areas with colder climates, such as the Niagara wine region in Ontario, Canada. As a relatively new grape-growing region, information about its *terroir* is still needed. This includes not only characteristics of the growing season but also the impact of conditions during the dormant season. As such, it is important to study the spatial patterns of common vineyard characteristics (yield, vine size, water status) as well as those involved with acclimation and cold hardiness. The objective of this study, therefore, is to define the spatial patterns of these variables for both Cabernet franc and Riesling throughout the Niagara region. With the use of GIS software, spatial patterns for soil moisture, leaf ψ, yield, and hardiness characteristics are mapped and compared between years. It is hypothesized that, in agreement with other studies, soil moisture, leaf ψ, yield, and bud survival will display temporally stable patterns. Additionally, it was hypothesized that bud LT_{50} measurements will also display temporal stability as well as characteristic monthly patterns from early (December) to late (February) winter, as expected based on literature.

3.2 Materials and Methods

3.2.1 Field and Laboratory Procedures

Six commercial vineyard blocks of both Riesling and Cabernet franc were chosen for this project. The blocks were located in five of the ten sub-appellations of the Niagara Peninsula, including: Niagara Lakeshore, Four Mile Creek, St. David's Bench, Lincoln Lakeshore (north and south sections), and Beamsville Bench [Vintners' Quality Alliance (VQA) 2009]. The general features of each vineyard can be found in Table A1. Approximately 75 sentinel vines were chosen per block with a smaller subset of these vines being chosen for leaf ψ, bud LT_{50}, bud survival, and monoterpene analysis (15 to 24 vines). The vines selected were healthy, and were representative of the vines within the block. A Raven Invicta 115 GPS (Global Positioning System) Receiver, Raven Industries (Sioux Falls, SD) (with 1.0 to 1.4 m accuracy) was used to delineate the shape of each vineyard block and geolocate each sentinel vine. The coordinates from each block were imported into Excel sheets and were visually represented using ArcGIS [Environmental Systems Research Institute (ESRI), Redlands, CA]. Soil moisture and leaf ψ measurements, and harvest procedures were completed following the same procedures as Reynolds et al. (2010a). Laboratory analysis of Cabernet franc samples was completed using the same procedures as Hakimi Rezaei et al. (2006); laboratory analysis of Riesling samples followed the work of Reynolds et al. (2010a,b).

3.2.2 Bud hardiness

i) Field work

Bud sampling was completed once in December, January, and February of 2010/2011 and 2011/2012. Samples were taken from the same vines that were used for leaf ψ observations. Cane samples were collected over a series of 3 days each month, with four blocks completed per day. Cane samples were removed from both sides of the vine over the 3-month period. Ideally, canes chosen for sampling were towards the exterior of the vine, were of approximately pencil thickness, and showed full periderm development. Where these criteria could not be met, the canes chosen were those most closely representing the growth of the vine. Interior cane samples that had potential for use in the upcoming growing season were not sampled. Cane samples were cut from the vine as close to the base of the cane as possible. After collection, cane samples were stored at 4 ^{o}C for up to one to two hours, until cutting and analysis could be completed.

ii) Differential Thermal Analysis

Differential thermal analysis (DTA) was used to analyse the bud hardiness of the sample vines. Before preparation of the buds for analysis, cane weights were taken using lab bench scales. Five undamaged buds were then excised from the canes using two opposing diagonal cuts: one along the leaf scar and the other close to the bud scale. A small amount of woody tissue was left attached to the bud in order to prevent damage to the diffusion barrier between the bud and the cane. This was done to better mimic environmental conditions and to enable the bud to supercool (Mills et al. 2006). The excised buds from each cane were placed together in one of 10 wells (4 cm x 4 cm x 15 mm) of a 33-cm x 23-cm x 7-cm tray (Mills et al. 2006). One well per tray was outfitted with a thermistor to detect the mean temperature of the tray. The other nine wells (containing the bud samples) were lined with silicon thermocouple devices to record the exothermic releases of heat upon bud death. The trays were loaded into two programmable freezers, with six trays in each freezer. Freezers were programmed to stabilize for 1 hr at 4 ^{o}C before dropping 4 ^{o}C/hr until a minimum temperature of -40 ^{o}C was reached. Upon analysis of the results, the median of the resulting exothermic peaks was chosen to represent the LT_{50} value (lethal temperature value at which 50% of the buds died).

iii) Bud survival

Bud survival assessments were made in February 2011 for the 2010 growing season, and in February/March 2012 for the 2011 growing season. Canes for survival assessment were chosen using the same criteria as bud hardiness samples. The bud survival canes were allowed to acclimate to room temperature for 24 to 48 hours before assessment. At this time, buds from positions 2 to11 (from base to tip) were shaved with a razor blade. Once the primary bud was exposed no further cuttings were made. A binary system was used to assess the buds. For live, green buds a value of 1 was given; for dead, brown buds a value of zero was given.

3.2.3 Statistics procedure

Statistical analysis was performed using XLStat (2012 version, Addinsoft SARL, New York, NY). In order to illustrate the temporal patterns of water metrics and bud hardiness, means and standard deviations were calculated for yield, leaf ψ, soil moisture, and all measurements of bud LT_{50}. Correlation tables were also used to analyse the relationships between bud survival and monthly bud LT_{50} values. Temperature and precipitation data were obtained from Environmental Canada at the Vineland Research Station.

3.2.4 GIS Mapping procedures

The GIS (geographic information system) program ArcGIS 10.1 [Environmental Systems Research Institute (ESRI), Redlands, CA] was used for all mapping procedures. Data were imported into ArcGIS from Microsoft Excel. The coordinates were projected using NAD UTM (Universal Transverse Mercator) Zone 17N. Data were interpolated using the (simple) kriging method. The interpolations chosen had the lowest error values and were rejected upon significant bulleting or other irregular geometric patterns. All interpolations were classified with 10 equal intervals and were displayed to a 2-m resolution. Morans I (autocorrelation) was used to investigate whether soil moisture, leaf ψ, and yield displayed dispersed (competitive), clustered, or random spatial patterns.

3.3 Results

Results in this chapter focus on the temporal stability of water metrics (soil moisture and leaf ψ and yield) and bud hardiness characteristics (bud LT_{50} values and bud survival). It also investigates monthly patterns of bud LT_{50} measurements and how they relate to the mean bud LT_{50} values. The following results are organized according to variable and grape variety, with individual information provided for each block. To support these results, tables providing the means and standard deviations of the variables are given (Table 3.1 – Table 3.4). Maps with Morans I results are also provided to support temporal patterns (Figs A1-A6 and A13-A18, and Fig. 3.1 – Fig. 3.16). The 2010/2011 winter season is referenced as the 2010 study year; the 2011/2012 winter season is referenced as the 2011 study year.

3.3.1 Temporal stability of soil moisture

i) Cabernet franc

For Cabernet franc blocks over the 2010 and 2011 growing seasons, five of the six locations showed temporal stability from visual assessment of the figures. Seven of the 12 data sets revealed clustered spatial patterns according to Morans I. Two of six blocks revealed clustered spatial patterns for both years (Buis Fig. A1, Cave Spring Fig. A5). The mean soil moisture values for the Buis block were 16.8 ± 2.6 % in 2010 and 15.9 ± 1.8 % in 2011 (Table 3.1). Alternating pockets of low and high soil moisture occurred in the south to north direction (Fig. A1). The George Cabernet franc block had great variation in soil moisture between years (19.4 ± 2.2 % in 2010, 12.9 ± 1.2 % in 2011) but did show a north/south division between low and high soil moisture in both 2010 and 2011 (Fig. A2). Kocsis also showed similar spatial patterns between years, with a northeast to southwest trend of high soil moisture (Fig. A3). Its mean soil moisture values for 2010 and 2011 were 14.3 ± 4 % and 10.6 ± 1.1 %, respectively. Both the Lambert and Lowrey blocks displayed north/south spatial trends for soil moisture (mean values in Table 3.1, Fig. A4 and Fig. A6), with low soil moisture values in the north and high values in the south. The Cave Spring vineyard showed greater variability in mean values between years and little similarity between the interpolations (Table 3.1, Fig. A5).

ii) Riesling

All six Riesling blocks showed temporal stability through 2010 and 2011 when assessed visually. Seven of the 12 data sets revealed clustered spatial patterns according to Morans I. The Buis block revealed clustered spatial patterns for both years (Fig. A13). Buis Riesling values were consistent between years (Table 3.2) with northern and southern pockets of low soil moisture (Fig. A13). The George block had large mean variations (20.2 % in 2010, 12.3 % in 2011) but was spatially consistent between years, with low values to the east and high values to the West (Fig. A14). Hughes showed low soil moisture in the north and south and high soil moisture through the middle of the block (Fig. A15). Soil moisture was higher in 2011 than in 2010 (Table 3.2). For the Lambert block, there were high soil moisture values throughout, with low soil moisture in the northwest corner for both years (Fig. A16). Mean soil moisture in 2010 was 16.5 ± 1.9 % and 20.6 ± 1.5 % in 2011. The Cave Spring block showed consistent mean values (Table 3.2) and patterns (Fig. A17) from 2010 to 2011. Southwest and northeast areas of high soil moisture were present both years. The Lowrey block had mean values of 15.3 % in 2010 and 13.9 % in 2011. Over both years, interpolations showed large areas of high soil moisture in the north and low soil moisture in the south (Fig. A18).

3.3.2 Temporal stability of leaf ψ

i) Cabernet franc

All six Cabernet franc blocks exhibited stable spatial trends for leaf ψ when assessed visually. Four of the 12 data sets revealed clustered spatial patterns, while two of the 12 revealed dispersed spatial patterns, according to Morans I. The George block had clustered spatial patterns for both years (Fig. A2).The Buis block had lower leaf ψ values to the north and higher leaf ψ to the south in both years (Fig. A1). The mean values were -12.6 ± 1.7 bar in 2010 and -9.3 ± 0.6 bar in 2011. The George block had consistent mean values in 2010 and 2011 (Table 3.1). It displayed a northwest to southeast increase in leaf ψ in both study years (Fig. A2). For the Kocsis block, there was little variance in values between years (Table 3.1), with a strip of low leaf ψ moving from north to south and high leaf ψ on the east and west boundaries (Fig. A3). Spatially, Lambert had low leaf ψ in the east and high leaf ψ in the west (Fig. A4). Its mean leaf ψ values in 2010 and 2011 were -10.06 ± 0.6 bar and -9.5 ± 1.1 bar, respectively. The Cave Spring block displayed a north/south spatial trend in both 2010 (-10.8 ± 0.7 bar) and 2011 (-11.7 ± 0.6 bar). It was more pronounced in 2011, with high leaf ψ in the north and low leaf ψ in the south (Fig. A5). The Lowrey block had consistent leaf ψ values in both 2010 and 2011 (Table 3.1) and displayed low leaf ψ to the west and high leaf ψ to the east (Fig. A6).

ii) Riesling

From visual assessments of the figures, three of six Riesling blocks showed temporally stable spatial patterns for leaf ψ measurements. Three of the 12 data sets revealed clustered spatial patterns, while one of the 12 had dispersed patterns, according to Morans I. The Hughes blocks had clustered spatial patterns for both years (Fig. A15).The Buis, George, and Lambert blocks did not have consistent spatial trends (Fig. A13, Fig. A14, and Fig. A16). The Hughes site was spatially stable, with low leaf ψ values to the north of the block and high leaf ψ to the south (Fig. A15; mean values of -10.9 ± 0.9 bar in 2010, -9.8 ± 1.1 bar in 2011). For Cave Spring, an east/west division of low/high leaf ψ was found for both years (Fig. A17). Mean values were lower in 2010 than in 2011 (Table 3.2). The Lowrey block had consistently low mean values for both 2010 and 2011 (Table 3.2) and also showed consistent spatial trends (Fig. A18). High leaf ψ was found to the north, moving southeast across the vineyard block, with low leaf ψ in the south.

3.3.3 <u>Temporal stability of yield</u>

i) Cabernet franc

Three of the six Cabernet franc sites displayed stable temporal relationships for yield between 2010 and 2011 when visually assessing the figures. The Lambert block did not have yield values in 2010. All blocks with data available in both years recorded lower mean yields in 2010 as compared to 2011 (Table 3.1). Four of the 11 data sets revealed clustered spatial patterns according to Morans I. The Buis block revealed clustered spatial patterns for both years (Fig. A1).The three consistent blocks (Buis, Kocsis, and Cave Spring) showed east/west directional trends. The Buis block revealed low yield to the west and high yield to the east (Fig. A1). Kocsis (Fig. A3) and Cave Spring (Fig. A5) showed high yield in the west and low yield in the east. The George block (mean yield values of 4.43 ± 0.93 kg in 2010, 5.66 ± 1.29 kg in 2011) showed some stable temporal trends such as high yields in the southern portion of the block (Fig. A2). The Lowrey block (2.67 ± 0.72 kg in 2010, 3.50 ± 0.92 kg) displayed east/west trends in 2010 and north/south trends in 2011 (Fig. A6).

ii) Riesling

Of the six Riesling blocks, four had stable spatial patterns when comparing 2010 and 2011 maps visually. Only one of the 12 data sets revealed clustered spatial patterns according to Morans I (George, 2011). The Buis block and the Lambert block were not stable (Fig. A13 and Fig. A16). All sites had higher yields in 2011 than in 2010. The George block had the most consistent yields (5.20 kg in 2010, 5.53 kg in 2011) and displayed a southwest/northeast division of high/low yield values (Fig. A14). The Hughes block had alternating patterns of high and low yield moving from north to south (Fig. A15). The Cave Spring block showed a temporal pattern of low yield values over much of the block, with higher yields in the southern portion (Fig. A17). In 2011, a low yield area was found to the east. This was not seen in 2010. The Lowrey block also had consistent mean yields (3.85 kg in 2010 and 3.91 kg in 2011) and displayed western pockets of low yield alternating with eastern pockets of high yield (Fig. A18).

3.3.4 Temporal stability of mean bud LT_{50} values

i) Cabernet franc

From visual assessments of the maps, four of the six blocks displayed similar temporal trends when comparing the winters of 2010 and 2011. No similar trends were seen between years for the Kocsis or Lambert blocks (Fig. 3.3, Fig. 3.4). Only one of the 12 data sets revealed clustered spatial patterns (Cave Spring, 2011), while one displayed dispersed spatial patterns (Buis, 2010), according to Morans I. All blocks reported lower mean bud LT_{50} values in 2010 (approximately -24 ^{o}C) than in 2011 (under -23 ^{o}C; Table 3.3). The lowest ambient temperatures for the region in 2010/2011 and 2011/2012 were -20 ^{o}C and -13.5 ^{o}C, respectively. For all six blocks studied, the highest monthly bud LT_{50} measurements were recorded in December of 2010 and 2011, with lower values being recorded in 2010 (Table 3.3). In general, the lowest bud LT_{50} measurements were found in January of both years (eight of 12 mean values). Exceptions included George (2010), Kocsis (2010), Cave Spring (2011), and Lowrey (2011), which all had February as their most hardy month. The lowest deviance from the mean predominantly occurred in

December while the greatest deviance occurred in January (Table 3.3). Eight of 12 sites showed strong correlations between monthly bud LT_{50} values and mean bud LT_{50} values (*Appendix II*), suggesting that spatial patterns were stable over the winter months. Therefore, vines which exhibited lower (higher bud LT_{50}) or higher (lower bud LT_{50}) bud hardiness did so throughout the winter season. The four blocks which did not agree with this statement were: George (2011), Kocsis (2010, 2011), and Lowrey (2011). In each case, December bud LT_{50} values did not correlate to the mean bud LT_{50} values.

The Buis block revealed north/south pockets of low bud LT_{50} values (Fig. 3.1). The George block showed a central pocket of low bud LT_{50} values for both years (Fig. 3.2). For the Cave Spring block, south-central areas of low values were temporally stable (Fig. 3.5). The Lowrey block had a distinct north/south trend in 2010 and 2011, with higher bud LT_{50} values in the north and lower bud LT_{50} values in the south (Fig. 3.6). Regarding temporally stable patterns between years for the months of December, January, and February, three of the six sites showed consistent patterns for December and January (Kocsis Fig. 3.3, Lambert Fig. 3.4, and Lowrey Fig. 3.6). February was the most consistent month, with five of six blocks showing stable trends when comparing 2010 and 2011, with the Buis block being the exception (Fig. 3.2 – Fig. 3.6). Of the blocks, Lambert and Lowrey showed the strongest temporal monthly patterns (Fig. 3.4 and Fig. 3.6, respectively). For Lambert, December showed southern and northern pockets with low bud LT_{50} values, January showed lower values to the west of the block, and February once again revealed northern and southern pockets of low bud LT_{50} values (Fig. 3.4). For the Lowrey block, alternating north/south pockets of low bud LT_{50} were found in December, and low bud LT_{50} values were found in the south end of the bock in both January and February (Fig. 3.6). This same trend was seen for mean bud LT_{50} measurements in both years.

ii) Riesling

Four of the six blocks had stable spatial patterns between the 2010 and 2011 winter seasons. No temporal trends were found for the George (Fig. 3.10) or Hughes (Fig. 3.11) block. Only one of the 12 data sets had dispersed spatial patterns (Buis, 2010), according to Morans I. All mean bud LT_{50} values were below -24 ^{o}C in 2010; mean values did not reach below approximately -23 ^{o}C in 2011 for any block (Table 3.4). For all six blocks studied, the highest monthly bud LT_{50} measurements were recorded in December of 2010 and 2011 (Table 3.4). The only exception was Hughes (2010). For seven of the 12 mean values, it can be seen that February was the month in which the lowest bud LT_{50} measurements were found. Exceptions included Cave Spring (2010), George (2010, 2011), and Lowrey (2011), which all had January as the month with the lowest values; Hughes (2010) recorded its lowest bud LT_{50} measurements in December. The lowest deviance from the mean predominantly occurred in December (six of 12 means) while the greatest deviance occurred in January (five of 12) and February (four of 12; Table 3.4). When comparing monthly bud LT_{50} values to the mean bud LT_{50}, correlation tests showed that nine of the 12 sites had strong correlations with the mean (*Appendix I*). The three blocks which did not agree with this statement were George (2011) and Hughes (2010, 2011). For the George block, the December bud LT_{50} values were not correlated with the mean bud $LT_{50.}$ For the Hughes site in 2010, December and January values were not correlated with the mean bud LT_{50}.

The Buis block displayed a north/south pattern of high and low mean bud LT_{50} measurements for both years, with a more east/west trend apparent in 2011 (Fig. 3.9). The Lambert block showed a north/south division as well, with lower mean measurements in the north, and higher ones in the south (Fig. 3.12). Although not a strong spatial relationship, the Cave Spring block showed large western areas of low bud LT_{50} values and easterly areas of higher values (Fig. 3.13). Minor temporal trends were seen for the Lowrey block, where a south-centrally located pocket of low bud LT_{50} was seen in both 2010 and 2011 (Fig. 3.14). Comparing monthly spatial trends between years, two blocks showed consistent patterns for December (Buis Fig. 3.9 and George Fig. 3.10), four blocks were consistent for January (George Fig. 3.10, Lambert Fig. 3.12, Cave Spring Fig. 3.13, and Lowrey Fig. 3.14), and four blocks were consistent for February (George Fig. 3.10, Hughes Fig. 3.11, Lambert Fig. 3.12, Cave Spring Fig. 3.13). Of the blocks studied, George, Lambert, and Cave Spring had the most temporally stable bud LT_{50} measurements (Fig. 3.10, Fig. 3.12, and Fig. 3.13, respectively). For the George block in December, low bud LT_{50} values were consistently found in the northwest and southeast; in January, values were low in the west and high in the east; in February, the northwest portion had low values and the southwest/northeast area had high bud LT_{50}

values. For the Lambert block, January showed low bud LT_{50} values in the northeast/east portion. In February, the low values shifted to the north in both years; this pattern was also seen in the mean bud LT_{50} interpolations. The Cave Spring block had northern sections of lower bud LT_{50} values and southern portions of higher values in January. In February, low areas were in the east and high in the west. The mean bud LT_{50} showed large westerly areas of low values and easterly areas of higher values (Fig. 3.13)

3.3.5 <u>Temporal stability of bud survival</u>

i) Cabernet franc

Bud survival showed consistent yearly spatial patterns for only 2 of 6 sites, with other blocks showing minor stable trends from visual assessment of the figures. The bud survival trend for the Buis block in 2010 was not similar to 2011 (Fig. 3.7). However, mean bud survival was comparable, being 95 % in 2010 and 93 % in 2011 (Table 3.3). The George block showed a northeast/southwest trend in both years, with higher survival rates being found in the northeast corner (Fig. 3.7). It was also comparable in survival percentages between years (89 % in 2010, 85 % in 2011). Stable temporal trends were also seen at the Kocsis vineyard which had a distinct eastern portion with lower survival. Northerly and southerly pockets of high survival could also be seen in both years (Fig. 3.7). Bud survival rates were 78 ± 30 % in 2010 and 86 ± 23 % in 2011 (Table 3.3). The Lambert block did not reveal any stable temporal trends for bud survival (Fig. 3.8). Survival rates were lower in 2010 than in 2011 (Table 3.3). The Cave Spring and Lowrey blocks did not show consistent spatial trends between years (Fig. 3.8). However, mean bud survival values were consistent for both blocks (Table 3.3).

ii) Riesling

Two blocks showed stable temporal trends over the 2010 and 2011 study period. For all the blocks studied, bud survival was greater in 2011 than in 2010, with differences ranging from 5 % to 13 % (Table 3.4). The Buis, George, Lambert, and Lowrey blocks did not show any consistent spatial trends for bud survival. The Hughes block revealed a strong north/south spatial trend for both years; higher bud survival was found in the north and lower bud survival was found in the far south end of the block (Fig. 3.15). The Cave Spring block had a southwest to northeast trend of high bud survival for both years. Larger areas of low bud survival were apparent in 2010 (Fig. 3.16).

3.4 Discussion

For new wine regions such as the Niagara Peninsula, which has only been growing *Vitis vinifera* cultivars in earnest for the past 30 years (Shaw 2005), it is important to illustrate that vineyard characteristics are temporally stable from year to year. These stable spatial patterns help to define the *terroir* of a region, allowing vineyard owners and winemakers to adjust their practices in order to take full advantage of the area in which they are producing wine. This two year study has shown that for Cabernet franc and Riesling cultivars temporally stable patterns of soil moisture, leaf ψ, yield, and mean bud LT50 measurements do exist. Of the variables studied, soil moisture, leaf ψ, and yield have been shown to influence berry size and composition (*Chapter 2*). Soil moisture, although displaying inconsistent relationships with leaf ψ, yield, and berry composition, was one of the most temporally stable variables studied, as five of six Cabernet franc blocks and all six Riesling blocks showed mostly North/South stable spatial patterns in both 2010 and 2011 (Figs. A1-A4, A6, and A13-A18). Morans I results also revealed significant spatial clustering of these patterns (14 of 24 data sets). Temporally stable patterns for soil moisture have previously been found in other studies (Reynolds et al. 2010a, Reynolds et al. 2010b, Vinnikov et al. 1996). In particular, Vinnikov et al. (1996) noted this stability in different ecosystems of Russia. Each ecosystem was unique but was individually stable over the 30 year time period of the study (Vinnikov et al. 1996). For the Niagara region, the stability of soil moisture is an important result since the area is known to have a variable climate from year to year (Shaw 2005). And, although the summer months of both 2010 and 2011 were relatively hot and dry, precipitation patterns were not consistent (Fig. A19 and A20). Therefore, the spatial patterns of soil moisture within the blocks studied may be identifiable even in years of drastically different weather conditions, supporting the creation of zones for managing proper soil moisture levels (irrigation, deficit irrigation).

Leaf ψ was also temporally stable, especially for Cabernet franc sites, where all six blocks revealed stable spatial patterns from 2010 to 2011 (Figs. A1-A6). Six of the 12 data sets also revealed significant spatial patterns, both dispersed and clustered. In contrast, only three of the six Riesling blocks showed this same amount of stability (Fig. A15, Fig. A17, and Fig. A18). Additionally, only four of the 12 data sets showing dispersed or clustered patterns. This suggests the existence of cultivar differences with regards to water use by the vines. The climate of the area could also have been a factor since the area is subject to high winds (Shaw 2005) which could affect the leaf ψ values within blocks, resulting in both north/south and east/west spatial patterns. This effect may especially influence Riesling, since the three blocks closest to the lake (Buis, George, Lambert, Fig. 2.22), which would be more prone to unstable weather due to the proximity of the lake (Shaw 2005), did not have temporally stable patterns. Those closer to the escarpment (Hughes, Cave Spring, Lowrey), however, did. Regardless of the direction in which the stability occurs, leaf ψ, as with other findings, was temporally stable over time (Reynolds et al. 2010a, Reynolds et al. 2010b). The stability of soil moisture and leaf ψ is especially important when reviewing Table 3.1 and Table 3.2 since mean values changed between years for many sites. In addition, some blocks had higher mean values in 2010 while others report higher values in 2011. This may be due, once again, to the volatile weather during the humid summer months where isolated systems produce the majority of the precipitation that falls, affecting water use by the vine (Shaw 2005).

Yield was fairly consistent between years, with higher yields found in all blocks in 2011 (Table 3.1 and 3.2). However, Morans I analysis suggests that only four of 11 Cabernet franc data sets and one of 12 Riesling data sets had significant spatial patterns. These results agree with past research done by Bramley and Hamilton (2004) and Reynolds et al. (2007) who found that yield was not always consistent between years. Bramley and Hamilton (2004) cited weather abnormalities as possible factors for widespread low yields at their Coonawarra study site, and frost damage for the variance in patterns between 2000 to 2001 and 2002 to 2003 at their Clare Valley site. This may also be the case for differences in Cabernet franc and Riesling yield patterns. By reviewing Fig. A20, the spring and fall of 2011 had much greater amounts of precipitation compared to 2010. This is especially paramount in the fall as berries are ripening, since it has been noted that excess moisture during the fall months promotes greater berry expansion (van Leeuwen and Seguin 2006). This occurs at a faster rate than solute accumulation (van Leeuwen and Seguin 2006), agreeing with previously stated relationships that yield was negatively related to many berry composition variables in both red and white varieties (*Chapter 2*).

As with yield, mean bud LT_{50} showed stable temporal patterns for most blocks. Two thirds of both Cabernet franc (Buis Fig. A1, George Fig. A2, Cave Spring Fig. A5, and Lowrey Fig. A6) and Riesling blocks (Buis Fig. A13, Lambert Fig. A16, Cave Spring Fig. A17, and Lowrey Fig. A18) showed stable temporal patterns between years, with only three of the 24 data sets revealing significant spatial patterns using Morans I analysis. Over all blocks, mean bud LT_{50} values were approximately a degree cooler in 2010/2011 as compared 2011/2012. This increase in hardiness was corroborated by mean monthly temperatures which revealed that 2010/2011 was, on average, a much cooler winter (Fig. A19). For Cabernet franc, these weather conditions seemed to affect blocks within the Plains region the most (Kocsis Fig. A3 and Lambert Fig. A4) since these were the only blocks with inconsistent patterns between winter seasons. Effects on Riesling were more widespread, with blocks near the lake and on the plain both with non-stable patterns. As with yield, weather events could have influenced mean bud LT_{50} patterns since research has shown that the hardiness of grapevines is dependent on ambient temperatures (Bramley and Hamilton 2004, Fennell 2004, Ferguson et al. 2011, Hubácová 1996, Zabadal et al. 2007).

The temporal stability of mean bud LT_{50} is supported by monthly patterns (Fig. 3.1 to Fig. 3.6 and Fig. 3.9 to Fig. 3.14). Cultivar differences do become apparent, as expected in literature (Clore et al. 1974, Lenne et al. 2010, Lisek 2007, Zabadal et al. 2007). Both cultivars experienced the lowest degree of hardiness in December when temperatures are still dropping (Fig. A19). However, Cabernet franc reached its maximum hardiness in January as compared to February for Riesling (Table 3.3 and Table 3.4). These months also showed the greatest variability between vines but also the greatest amount temporal stability. This suggests that the same vines reach the same relative hardiness levels from year to year, translating into greater temporal stability for mean bud LT_{50} patterns. Blocks which exemplify these patterns include the Lambert (Fig. 3.4 and Fig. 3.12) and Lowrey (Fig. 3.6 and Fig. 3.13) Cabernet franc and Riesling blocks. However, bud survival was not found to be temporally stable for either Cabernet franc or Riesling (Fig. 3.7, 3.8, 3.15, and 3.16). As with yield and mean bud LT_{50}, exceptional circumstances can skew temporal trends. Bud survival is extremely sensitive to microclimate effects, such as cold pockets, or inadvertent cane damage which can kill primary buds with little or no relationship to bud hardiness. The temporal results for bud survival do support the trend of cultivar differences between Cabernet franc and Riesling, however. Cabernet franc, which reached maximum hardiness in January, displayed greater survival percentages than Riesling, with many buds being able to survive the cold of the 2010/2011 winter season (Table 3.3 compared to Table 3.4). All Riesling blocks, on the other hand, displayed lower survival percentages during the cold 2010/2011 season as compared to the warmer 2011/2012.

Kriging interpolations were successful in determining the spatial patterns of the variables outlined above. However, the maximum and minimum values stated on the maps frequently did not match those found in Table 3.1 to Table 3.4. These same issues are addressed by Bramley (2005) and Bramley et al. (2011) who state that kriging, in order to accurately interpolate trends, "smoothes" the data, resulting in tighter ranges of values. However, overall trends expressed by the maps are more important and do indeed reflect areas of high and low values throughout vineyard blocks (Bramley 2005, Bramley et al. 2011). Additionally, some difficulties were encountered in interpolating variables with limited data sets, resulting in "bulleting" or irregular patterns that could not be removed without significant alterations to trends (for example, bud LT_{50} values or survival percentages). Bramley (2005) expresses the importance of sampling design when executing GIS methods. Points spaced closer together are more likely to represent variations within the vineyard (Bramley 2005). Therefore, future studies should allow for a greater number of more closely spaced spatial data points in order to increase the precision of the interpolation method.

3.5 Conclusions

The hypothesis of this study was that spatial patterns of soil moisture, leaf ψ, yield, mean bud LT_{50}, and bud survival would be temporally stable over the two year study period. Additionally, it was expected that monthly bud LT_{50} patterns would also show temporal trends. With the exception of bud survival, this hypothesis was supported by the results. Strong patterns of temporal stability existed for soil moisture, leaf ψ, and yield, with cultivar differences appearing in leaf ψ trends. These results agreed with past literature and were supported by weather patterns over the two years. Mean bud LT_{50} was also found to be temporally stable, with cultivar differences apparent when reviewing these patterns in conjunction with monthly bud LT_{50} patterns and bud survival. Although bud survival did not show strong temporal trends, it did show that Cabernet franc blocks had better rates of survival than their Riesling counterparts because they reached maximum hardiness more quickly. Discoveries in this study therefore suggest that weather is not the only factor that affects hardiness but that there are temporal patterns which exist within a vineyard block independent of temperature. In addition, the *terroir* of the Niagara Peninsula supports the existence of cold hardy cultivars which display stable temporal patterns for soil moisture, leaf ψ, yield, and (most importantly) bud hardiness.

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3.7 List of Figures

Figure 3.10 Maps of monthly and mean bud LT_{50} values for George Riesling in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT_{50}. Bottom: 2011 maps for December, January, February, and mean bud LT_{50}. Morans I results for 2010 mean bud LT_{50}: z-score = 0.7977 (random); Morans I results for 2011 mean bud LT_{50}: z-score =-0.4478 (random).

Figure 3.11 Maps of monthly and mean bud LT50 values for Hughes Riesling in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT50. Bottom: 2011 maps for December, January, February, and mean bud LT50. Morans I results for 2010 mean bud LT_{50}: z-score = -0.9200 (random); Morans I results for 2011 mean bud LT_{50}: z-score = -1.1839 (random).

Figure 3.12 Maps of monthly and mean bud LT50 values for Lambert Riesling in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT50. Bottom: 2011 maps for December, January, February, and mean bud LT50. Morans I results for 2010 mean bud LT_{50}: z-score = 1.4193 (random); Morans I results for 2011 mean bud LT_{50}: z-score = -0.0772 (random).

Figure 3.13 Maps of monthly and mean bud LT50 values for Cave Spring Riesling in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT50. Bottom: 2011 maps for December, January, February, and mean bud LT50. Morans I results for 2010 mean bud LT_{50}: z-score = 0.5672 (random); Morans I results for 2011 mean bud LT_{50}: z-score = -1.2599 (random).

Figure 3.14 Maps of monthly and mean bud LT50 values for Lowrey Riesling in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT50. Bottom: 2011 maps for December, January, February, and mean bud LT50. Morans I results for 2010 mean bud LT_{50}: z-score = 0.7322 (random); Morans I results for 2011 mean bud LT_{50}: z-score = -1.4734 (random).

Figure 3.15 Maps of bud survival for Buis, George, and Hughes Riesling blocks in 2010 and 2011. a) Buis block, top 2010, bottom 2011; b) George block, top 2010, bottom 2011; c) Hughes block, top 2010, bottom 2011.

Figure 3.16 Maps of bud survival for Lambert, Cave Spring, and Lowrey Riesling blocks in 2010 and 2011. a) Lambert block, top 2010; b) Cave Spring block, top 2010, bottom 2011; c) Lowrey block, top 2010, bottom 2011.

Supplemental Figures Relevant to this Chapter

Figure A1 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Buis Cabernet franc block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and vine size. Bottom row: 2011 soil moisture, leaf ψ, yield, and vine size.

Figure A2 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the George Cabernet franc block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and vine size. Bottom row: 2011 soil moisture, leaf ψ, yield, and vine size.

Figure A3 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Kocsis Cabernet franc block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and vine size. Bottom row: 2011 soil moisture, leaf ψ, yield, and vine size.

3.8 Tables and Figures

Table 3.1: Mean values and standard deviation (±) of soil moisture, leaf ψ, and yield for Cabernet franc blocks in 2010 and 2011.

Block	Soil Moisture (%)	±	Leaf ψ (bar)	±	Yield (kg)	±
Buis 2010	16.8	2.6	-12.6	0.5	3.93	1.15
Buis 2011	15.9	1.8	-9.3	0.6	4.48	1.22
Cave Spring 2010	20.7	2.0	-10.8	0.7	2.88	0.95
Cave Spring 2011	15.5	1.3	-11.7	0.7	4.67	1.15
George 2010	19.4	2.2	-10.9	0.9	4.43	0.93
George 2011	12.9	1.2	-10.5	0.7	5.66	1.29
Kocsis 2010	14.3	4.0	-12.3	0.8	1.47	0.83
Kocsis 2011	10.6	1.1	-12.7	0.8	2.13	0.78
Lambert 2010	16.9	1.6	-10.0	0.6	-	-
Lambert 2011	15.2	1.3	-9.5	1.1	4.37	1.05
Lowrey 2010	14.8	2.0	-11.3	0.7	2.67	0.72
Lowrey 2011	13.8	1.9	-11.3	0.5	3.50	0.92

Table 3.2: Mean values and standard deviation (±) of soil moisture, leaf ψ, and yield for Riesling blocks in 2010 and 2011.

Block	Soil Moisture (%)	±	Leaf ψ (bar)	±	Yield (kg)	±
Buis 2010	14.3	2.2	-9.0	1.3	4.27	1.26
Buis 2011	13.9	2.3	-8.4	1.1	6.92	1.64
Cave Spring 2010	11.6	1.6	-8.8	0.4	3.78	1.62
Cave Spring 2011	10.9	0.9	-9.9	0.9	5.59	1.75
George 2010	20.2	1.2	-9.7	1.1	5.20	1.29
George 2011	12.3	1.2	-8.8	0.8	5.53	1.68
Hughes 2010	15.5	3.5	-10.9	0.9	5.40	0.92
Hughes 2011	18.5	2.6	-9.8	1.1	6.53	1.26
Lambert 2010	16.5	1.9	-10.4	0.7	4.24	1.09
Lambert 2011	20.6	1.5	-7.6	0.5	3.43	1.49
Lowrey 2010	15.3	1.4	-11.0	0.5	3.85	0.90
Lowrey 2011	13.9	1.8	-11.1	0.6	3.91	1.07

Table 3.3: Mean values and standard deviation (±) of monthly bud LT_{50}, mean bud LT_{50}, and bud survival for Cabernet franc blocks in 2010 and 2011.

Block	Dec (°C)	±	Jan (°C)	±	Feb (°C)	±	Mean Bud LT_{50} (°C)	±	Bud Survival (%)	±
Buis 2010	-24.03	1.01	-24.69	1.08	-24.16	0.70	-24.14	0.52	95	7
Buis 2011	-21.38	0.96	-23.33	0.96	-21.71	0.99	-22.14	0.69	93	14
Cave Spring 2010	-23.00	1.30	-24.01	1.50	-24.50	1.33	-23.84	1.19	89	12
Cave Spring 2011	-21.23	0.90	-23.57	0.98	-20.68	0.92	-21.83	0.72	88	10
George 2010	-23.79	1.24	-25.02	1.54	-25.07	0.78	-24.63	0.93	89	14
George 2011	-22.09	0.64	-23.71	1.55	-22.92	1.01	-22.91	0.71	85	14
Kocsis 2010	-23.25	1.24	-24.16	1.68	-25.17	1.25	-24.20	0.91	78	30
Kocsis 2011	-20.98	0.86	-22.52	1.25	-18.78	1.27	-20.86	0.79	86	23
Lambert 2010	-23.42	1.10	-25.20	1.64	-24.44	0.93	-24.33	0.93	83	13
Lambert 2011	-22.04	0.90	-22.94	0.91	-22.62	0.91	-22.54	0.61	88	11
Lowrey 2010	-22.78	1.16	-24.58	2.26	-24.23	1.20	-23.84	1.06	79	19
Lowrey 2011	-22.66	0.87	-22.79	1.47	-23.00	0.84	-22.90	0.84	80	24

Table 3.4: Mean values and standard deviation (±) of monthly bud LT_{50}, mean bud LT_{50}, and bud survival for Riesling blocks in 2010 and 2011.

Block	Dec (°C)	±	Jan (°C)	±	Feb (°C)	±	Mean Bud LT_{50} (°C)	±	Bud Survival (%)	±
Buis 2010	-23.56	0.77	-24.10	1.02	-24.54	0.96	-24.11	0.73	81	16
Buis 2011	-20.34	1.29	-23.81	1.14	-24.62	0.77	-22.99	0.85	86	16
Cave Spring 2010	-24.01	1.32	-24.43	1.69	-23.49	1.56	-24.04	1.23	76	25
Cave Spring 2011	-20.44	1.67	-24.17	1.12	-24.57	1.20	-23.48	1.33	89	11
George 2010	-24.31	1.64	-25.11	0.92	-24.54	0.99	-24.65	0.90	87	10
George 2011	-21.54	0.76	-24.58	1.21	-22.52	1.52	-23.00	0.71	93	8
Hughes 2010	-24.45	1.17	-24.43	1.08	-24.30	1.32	-24.40	0.67	70	27
Hughes 2011	-21.98	0.78	-23.27	0.98	-24.01	1.10	-23.20	0.70	78	23
Lambert 2010	-23.55	1.36	-24.38	2.01	-25.72	1.14	-24.51	1.21	66	22
Lambert 2011	-22.22	1.00	-23.16	1.09	-23.50	0.95	-22.96	0.62	-	-
Lowrey 2010	-23.62	1.23	-24.58	2.50	-25.14	1.30	-24.37	1.10	73	11
Lowrey 2011	-22.75	0.93	-23.70	1.03	-23.54	1.33	-23.32	0.69	84	15

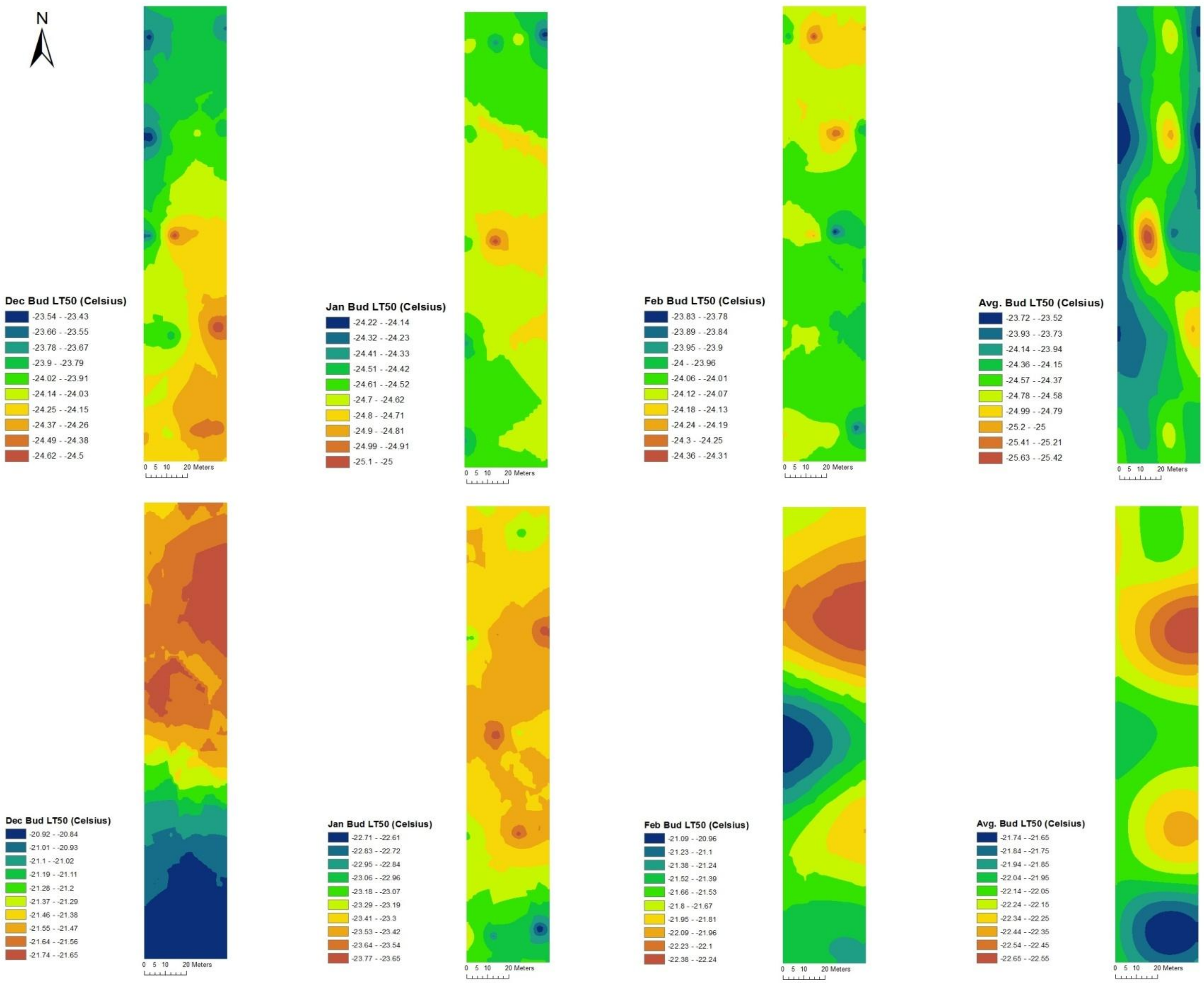

Figure 3.1 Maps of monthly and mean bud LT50 values for Buis Cabernet franc in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT50. Bottom: 2011 maps for December, January, February, and mean bud LT_{50}. Morans I results for 2010 mean bud LT_{50}: z-score = -1.8356 (dispersed); Morans I results for 2011 mean bud LT_{50}: z-score = 1.0170 (random).

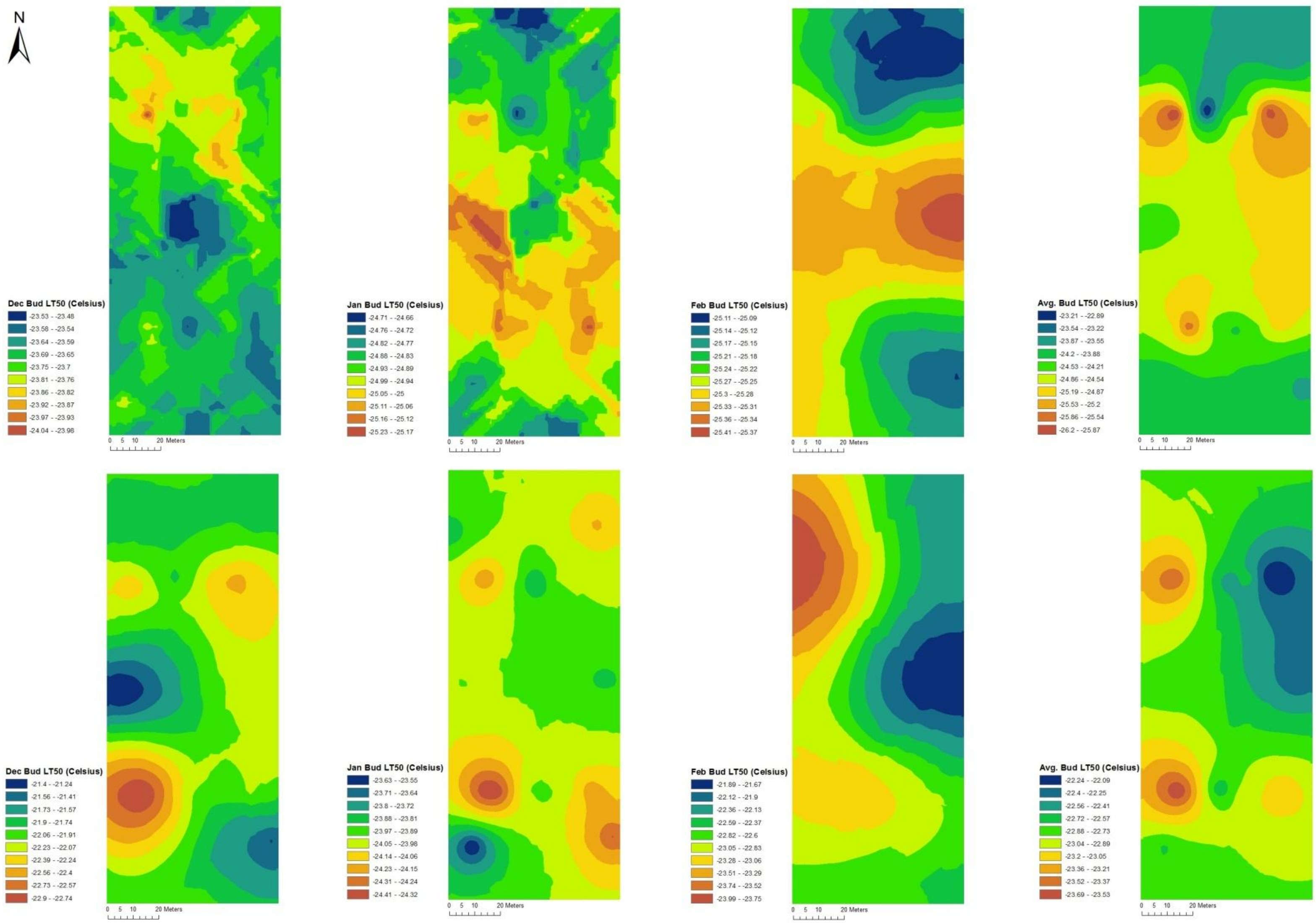

Figure 3.2 Maps of monthly and mean bud LT50 values for George Cabernet franc in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT50. Bottom: 2011 maps for December, January, February, and mean bud LT50. Morans I results for 2010 mean bud LT_{50}: z-score = 0.1368 (random); Morans I results for 2011 mean bud LT_{50}: z-score = 0.9569 (random).

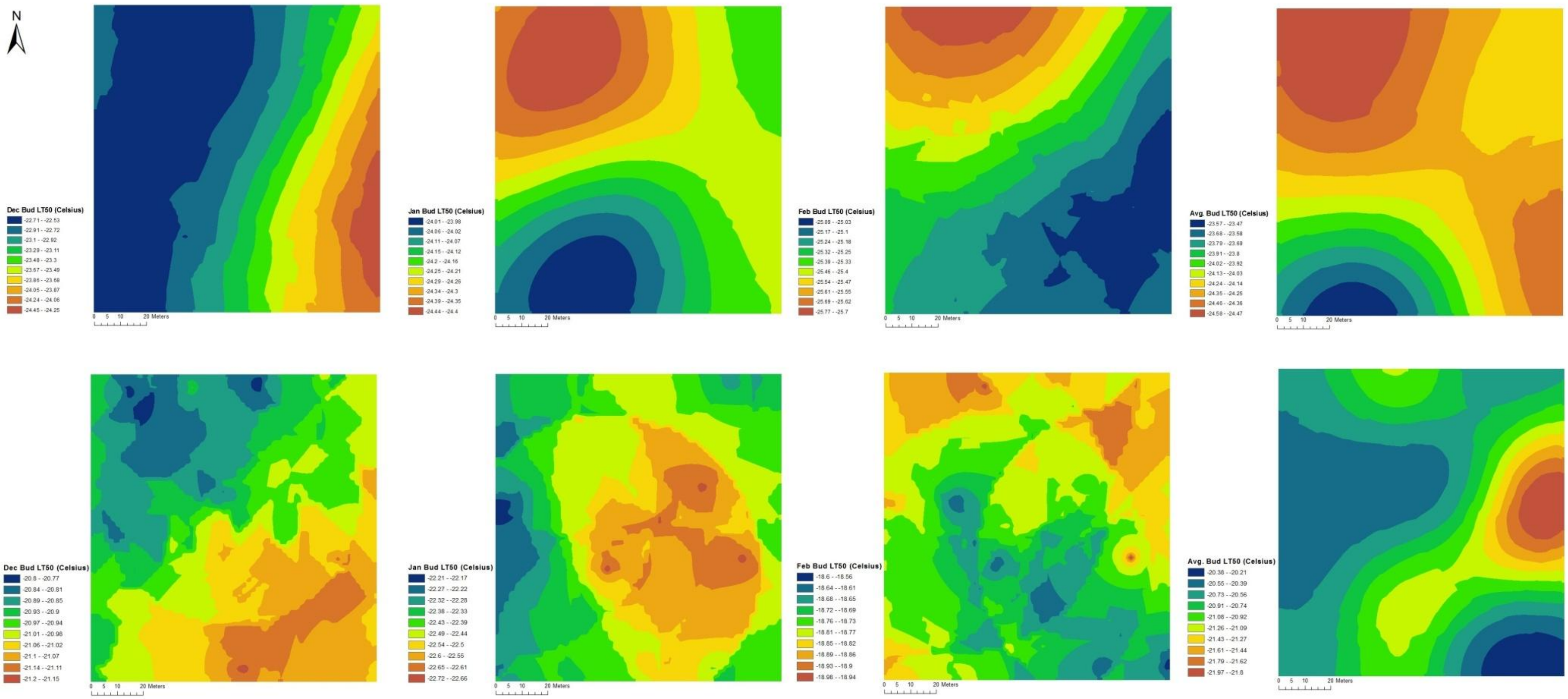

Figure 3.3 Maps of monthly and mean bud LT50 values for Kocsis Cabernet franc in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT50. Bottom: 2011 maps for December, January, February, and mean bud LT50. Morans I results for 2010 mean bud LT_{50}: z-score = 0.7961 (random); Morans I results for 2011 mean bud LT_{50}: z-score = 0.5025 (random).

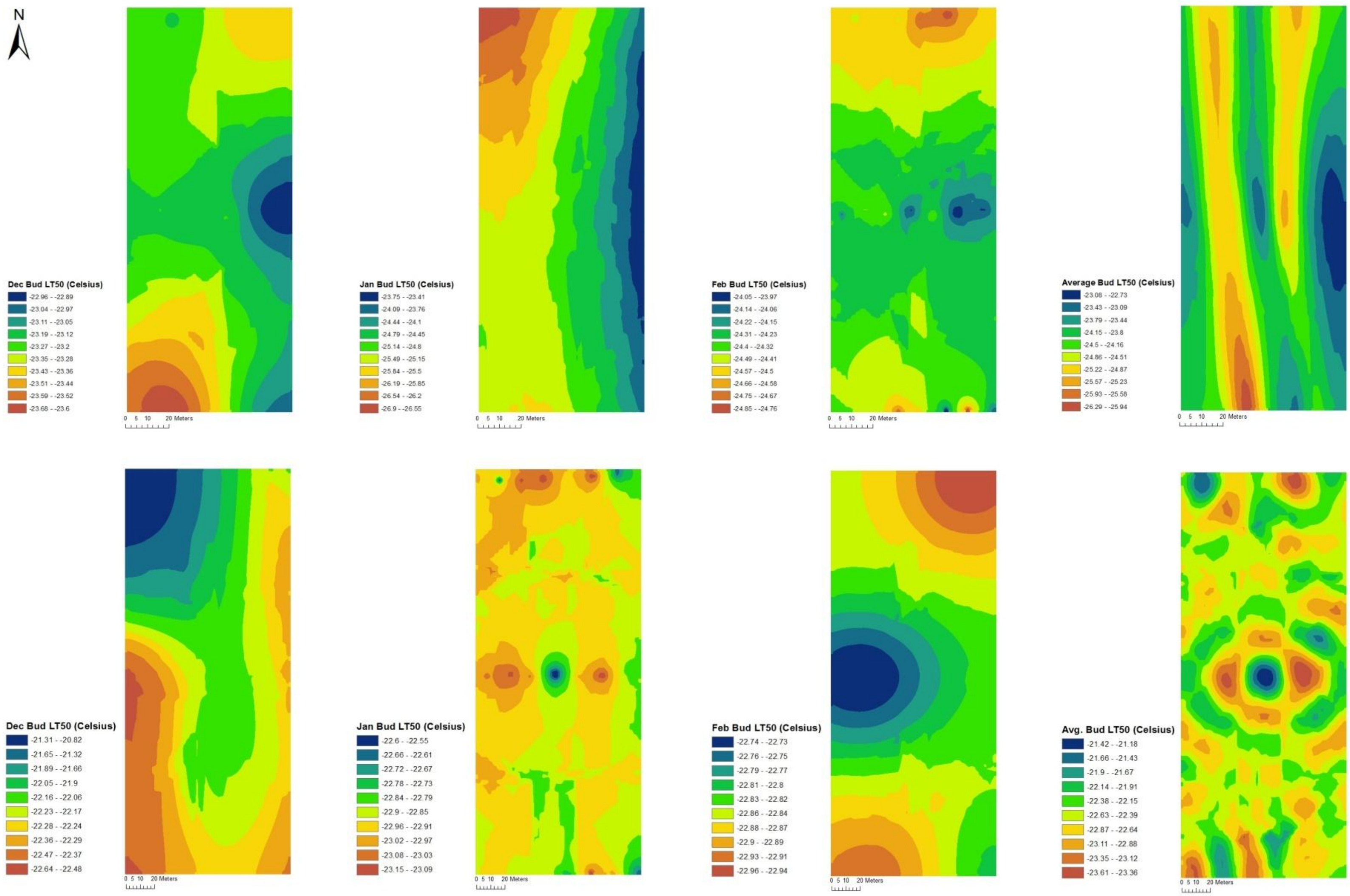

Figure 3.4 Maps of monthly and mean bud LT50 values for Lambert Cabernet franc in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT50. Bottom: 2011 maps for December, January, February, and mean bud LT50. Morans I results for 2010 mean bud LT_{50}: z-score = -0.5325 (random); Morans I results for 2011 mean bud LT_{50}: z-score = -1.5012 (random).

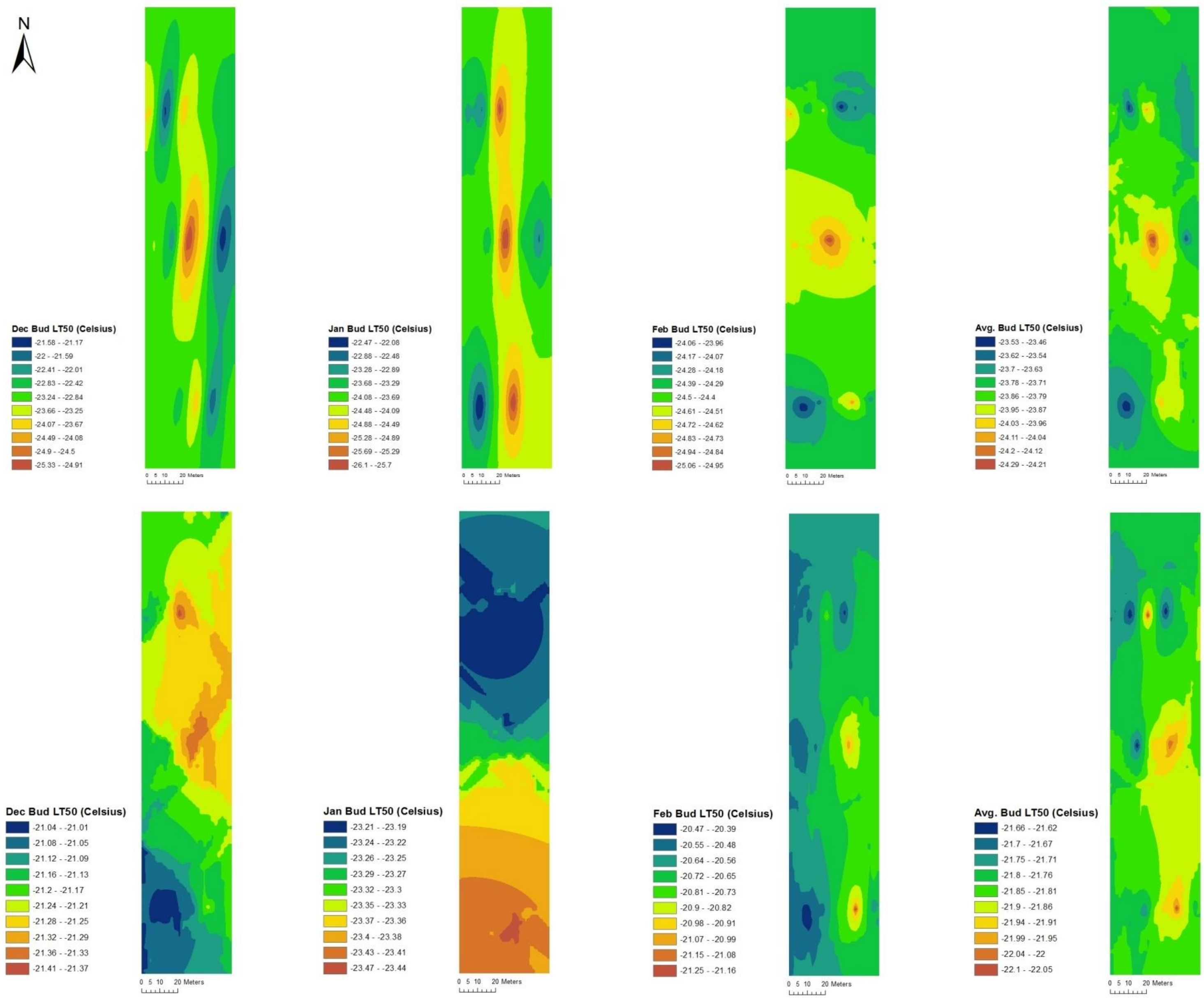

Figure 3.5 Maps of monthly and mean bud LT50 values for Cave Spring Cabernet franc in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT50. Bottom: 2011 maps for December, January, February, and mean bud LT50. Morans I results for 2010 mean bud LT_{50}: z-score = -1.8192 (random); Morans I results for 2011 mean bud LT_{50}: z-score = 7.9624 (clustered).

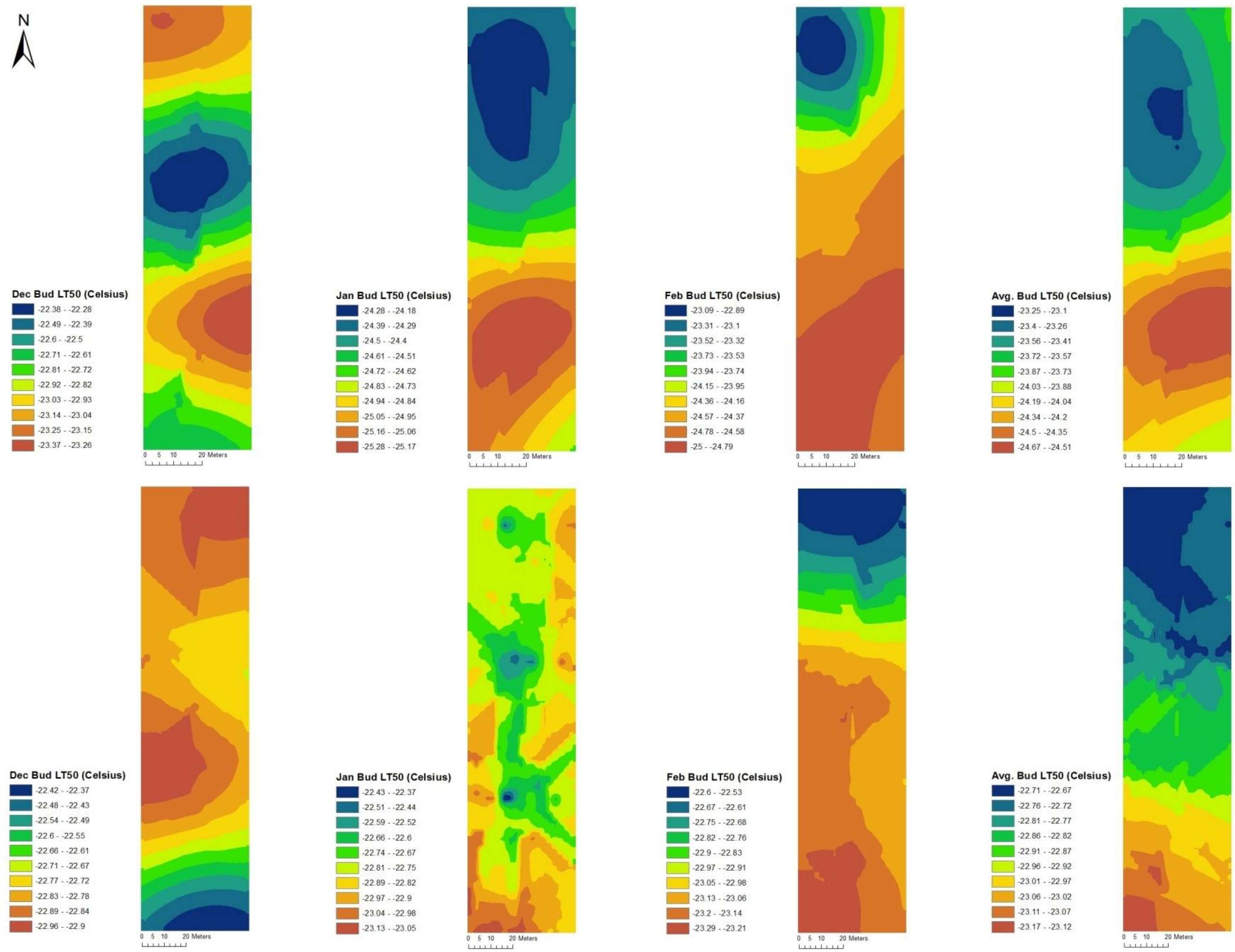

Figure 3.6 Maps of monthly and mean bud LT50 values for Lowrey Cabernet franc in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT50. Bottom: 2011 maps for December, January, February, and mean bud LT50. Morans I results for 2010 mean bud LT_{50}: z-score = 1.3547 (random); Morans I results for 2011 mean bud LT_{50}: z-score = -0.4790 (random).

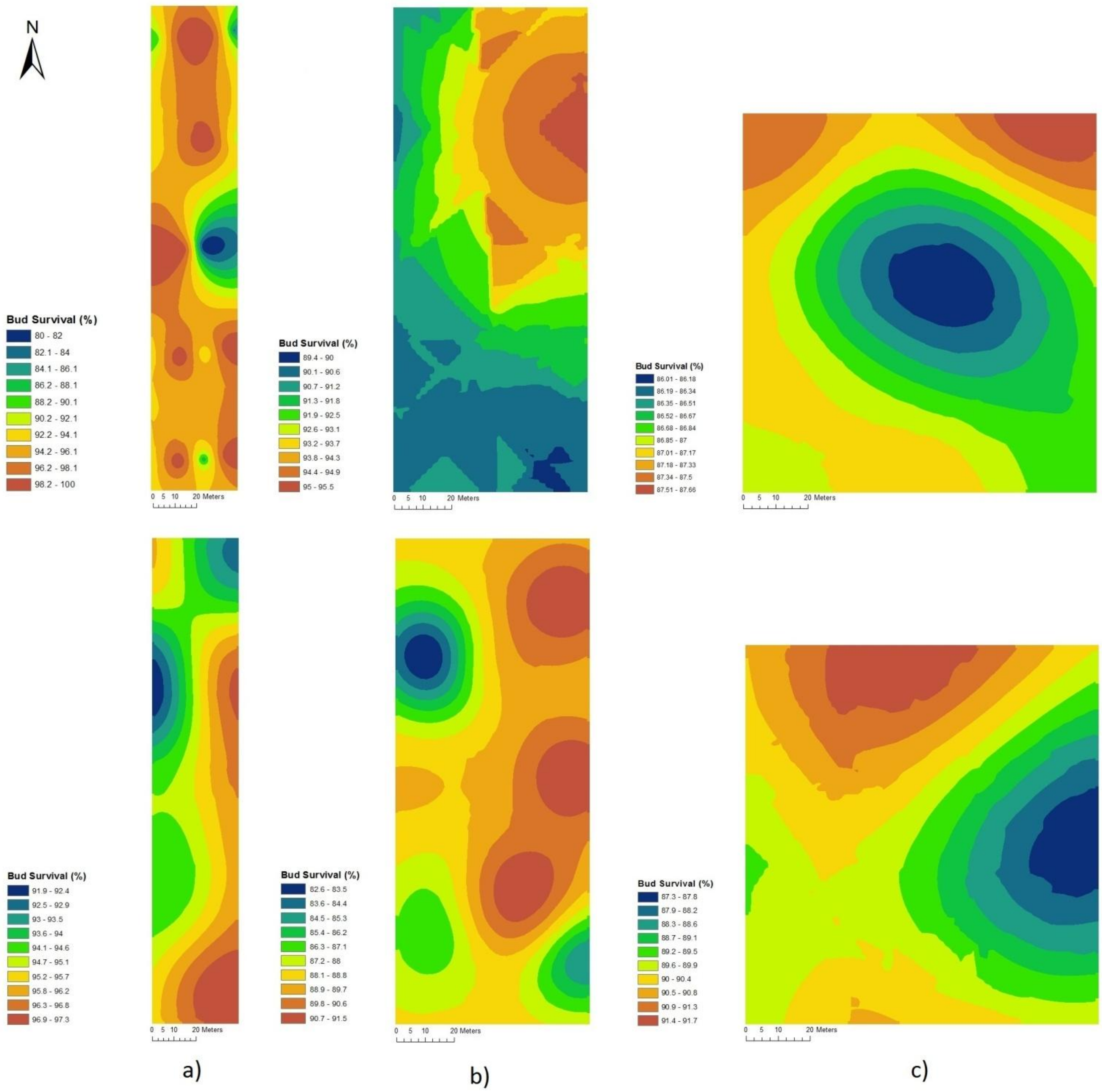

Figure 3.7 Maps of bud survival for Buis, George, and Kocsis Cabernet franc blocks in 2010 and 2011. a) Buis block, top 2010, bottom 2011; b) George block, top 2010, bottom 2011; c) Kocsis block, top 2010, bottom 2011.

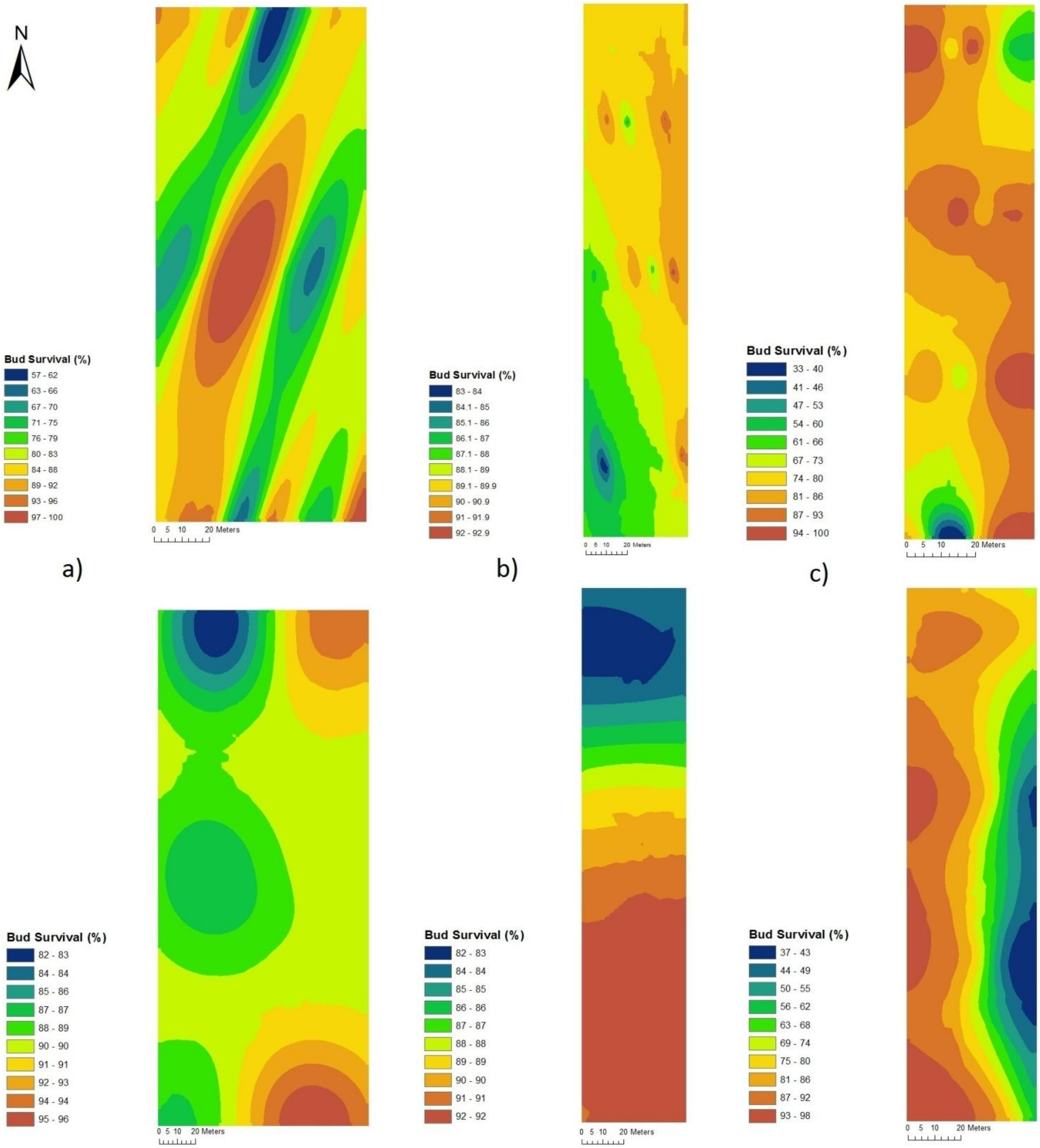

Figure 3.8 Maps of bud survival Lambert, Cave Spring, and Lowrey Cabernet franc blocks in 2010 and 2011. a) Lambert block, top 2010, bottom 2011; b) Cave Spring, top 2010, bottom 2011; Lowrey, top 2010, bottom 2011.

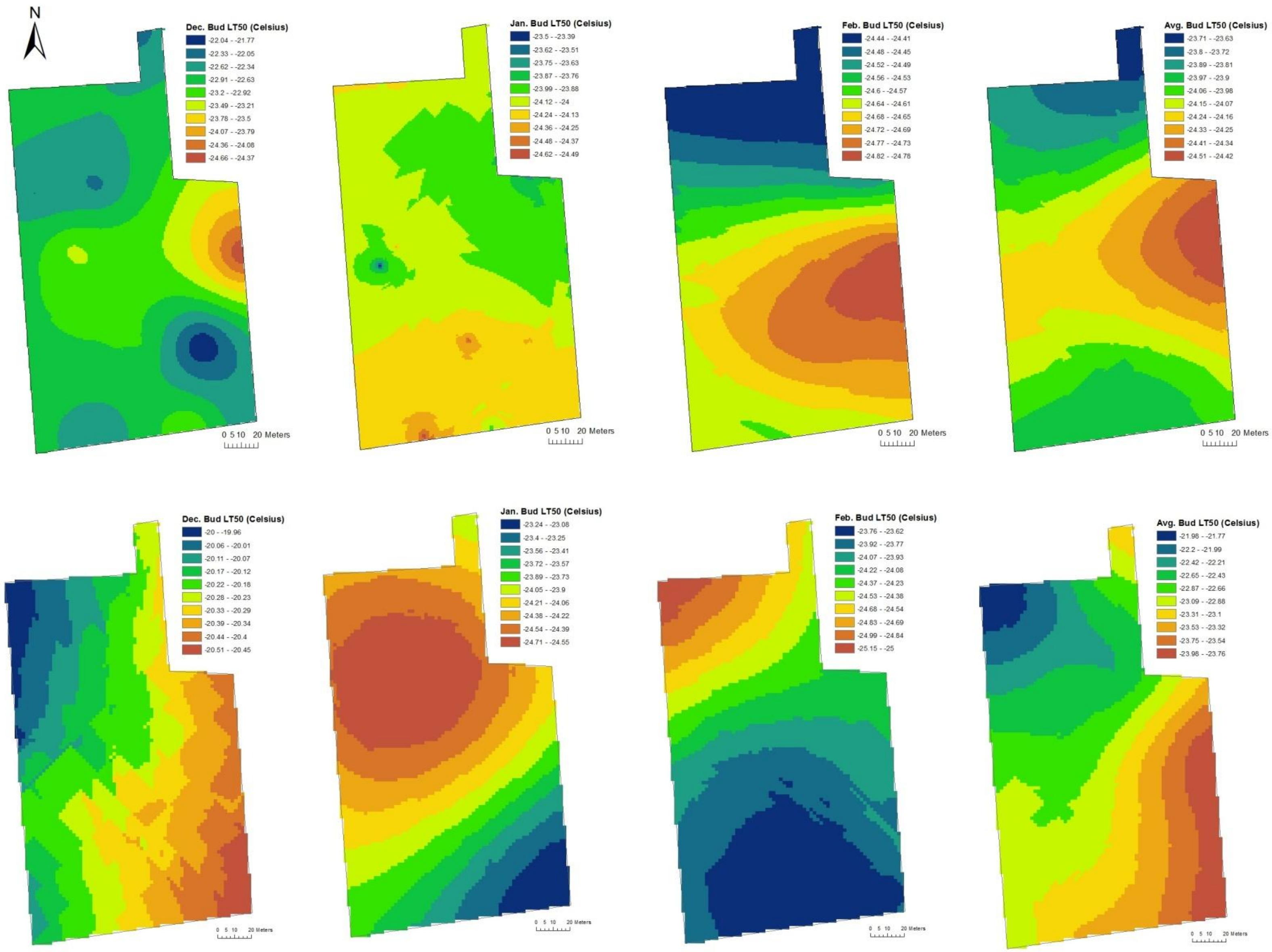

Figure 3.9 Maps of monthly and mean bud LT_{50} values for Buis Riesling in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT_{50}. Bottom: 2011 maps for December, January, February, and mean bud LT_{50}. Morans I results for 2010 mean bud LT_{50}: z-score = -2.1547 (dispersed); Morans I results for 2011 mean bud LT_{50}: z-score = 0.9793 (random).

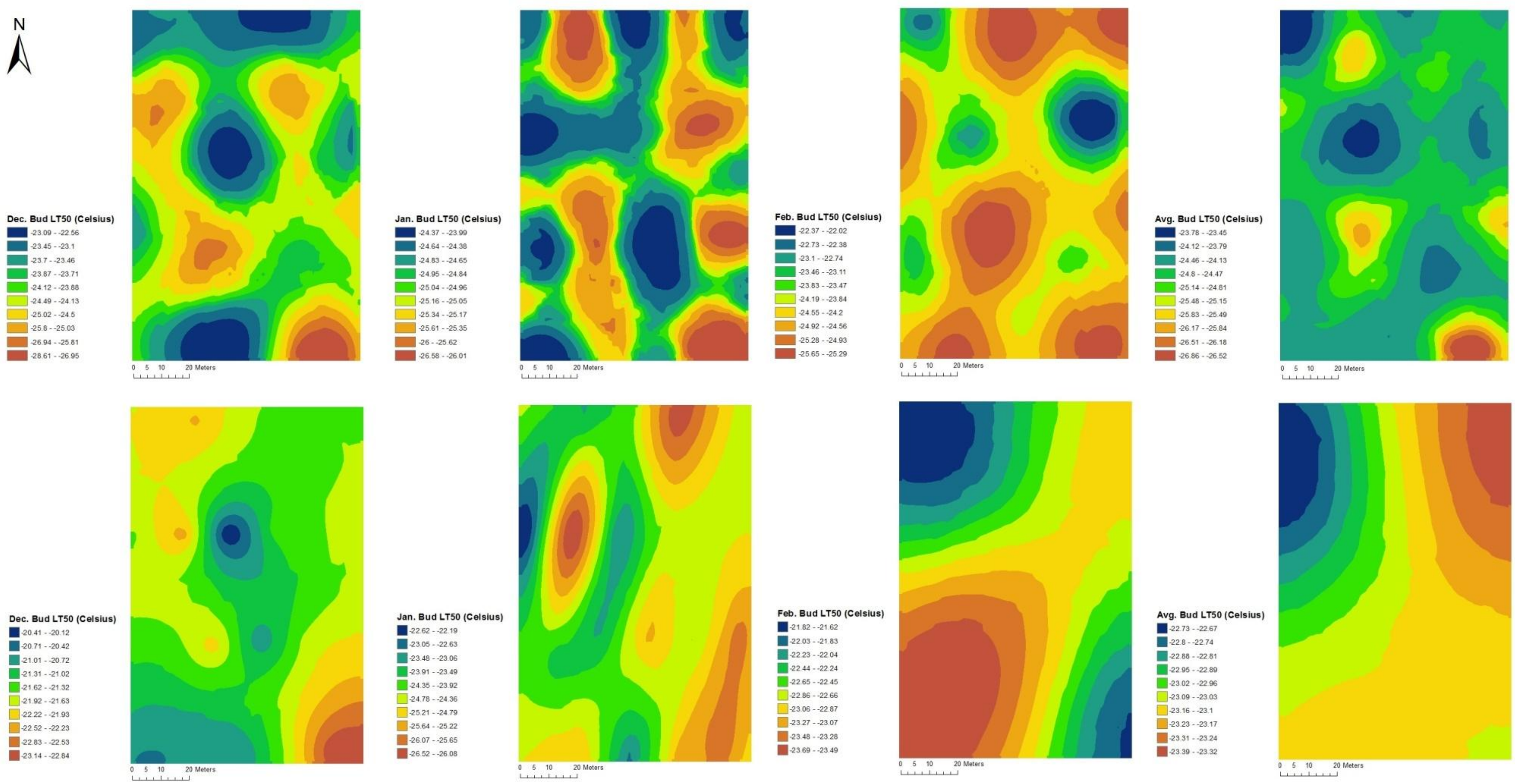

Figure 3.10 Maps of monthly and mean bud LT_{50} values for George Riesling in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT_{50}. Bottom: 2011 maps for December, January, February, and mean bud LT_{50}. Morans I results for 2010 mean bud LT_{50}: z-score = 0.7977 (random); Morans I results for 2011 mean bud LT_{50}: z-score = -0.4478 (random).

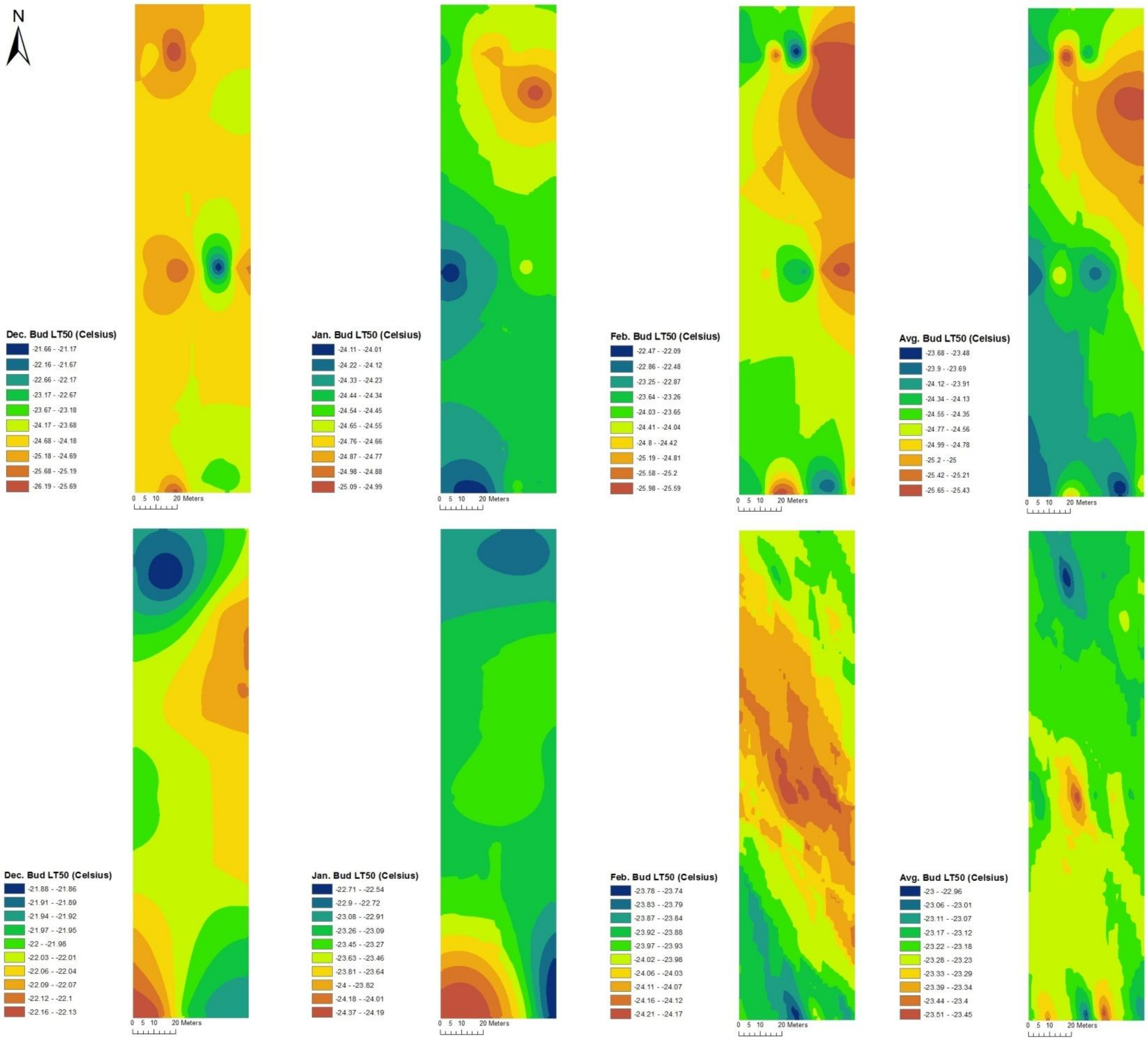

Figure 3.11 Maps of monthly and mean bud LT50 values for Hughes Riesling in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT50. Bottom: 2011 maps for December, January, February, and mean bud LT50. Morans I results for 2010 mean bud LT_{50}: z-score = -0.9200 (random); Morans I results for 2011 mean bud LT_{50}: z-score = -1.1839 (random).

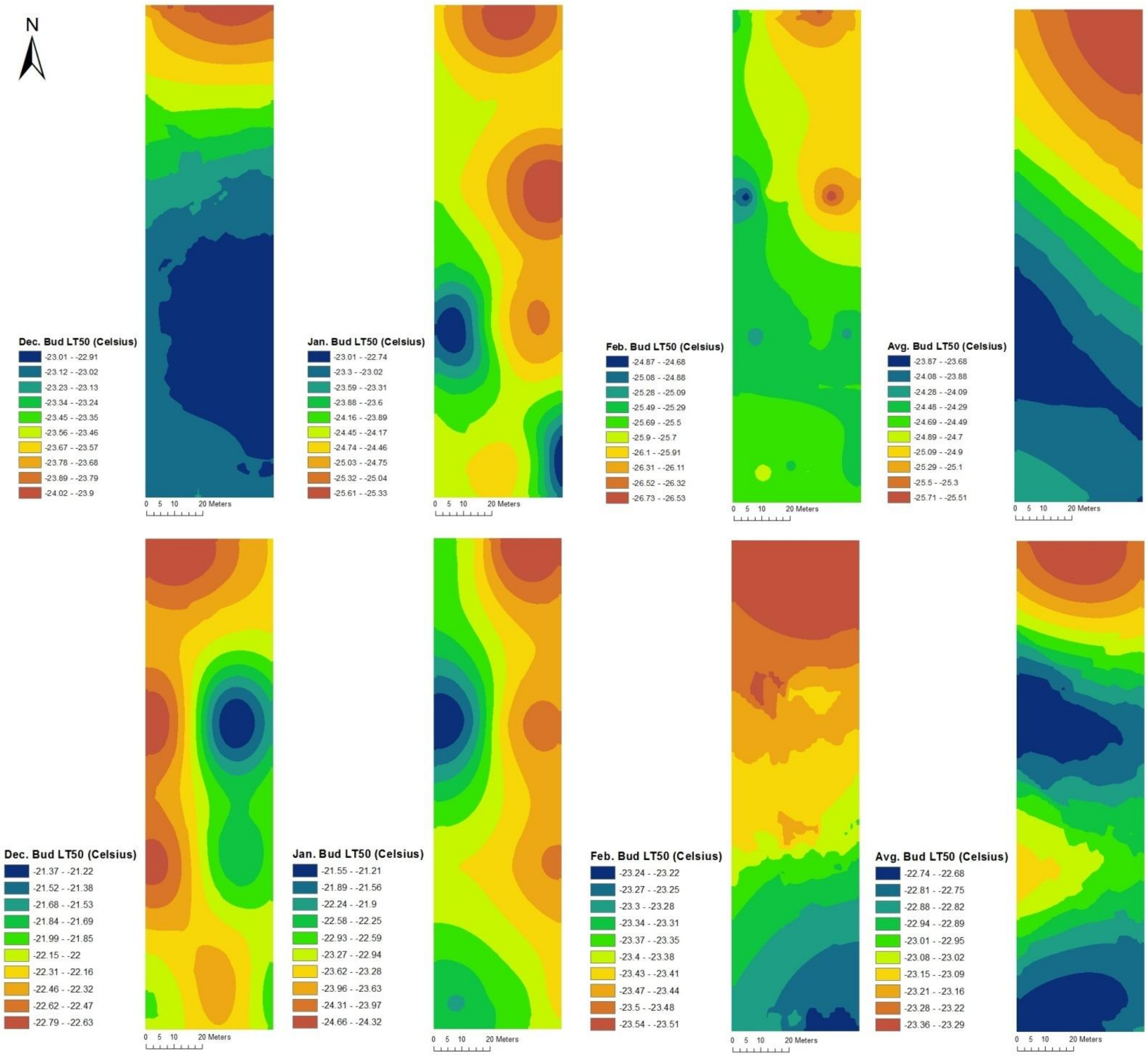

Figure 3.12 Maps of monthly and mean bud LT50 values for Lambert Riesling in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT50. Bottom: 2011 maps for December, January, February, and mean bud LT50. Morans I results for 2010 mean bud LT_{50}: z-score = 1.4193 (random); Morans I results for 2011 mean bud LT_{50}: z-score = -0.0772 (random).

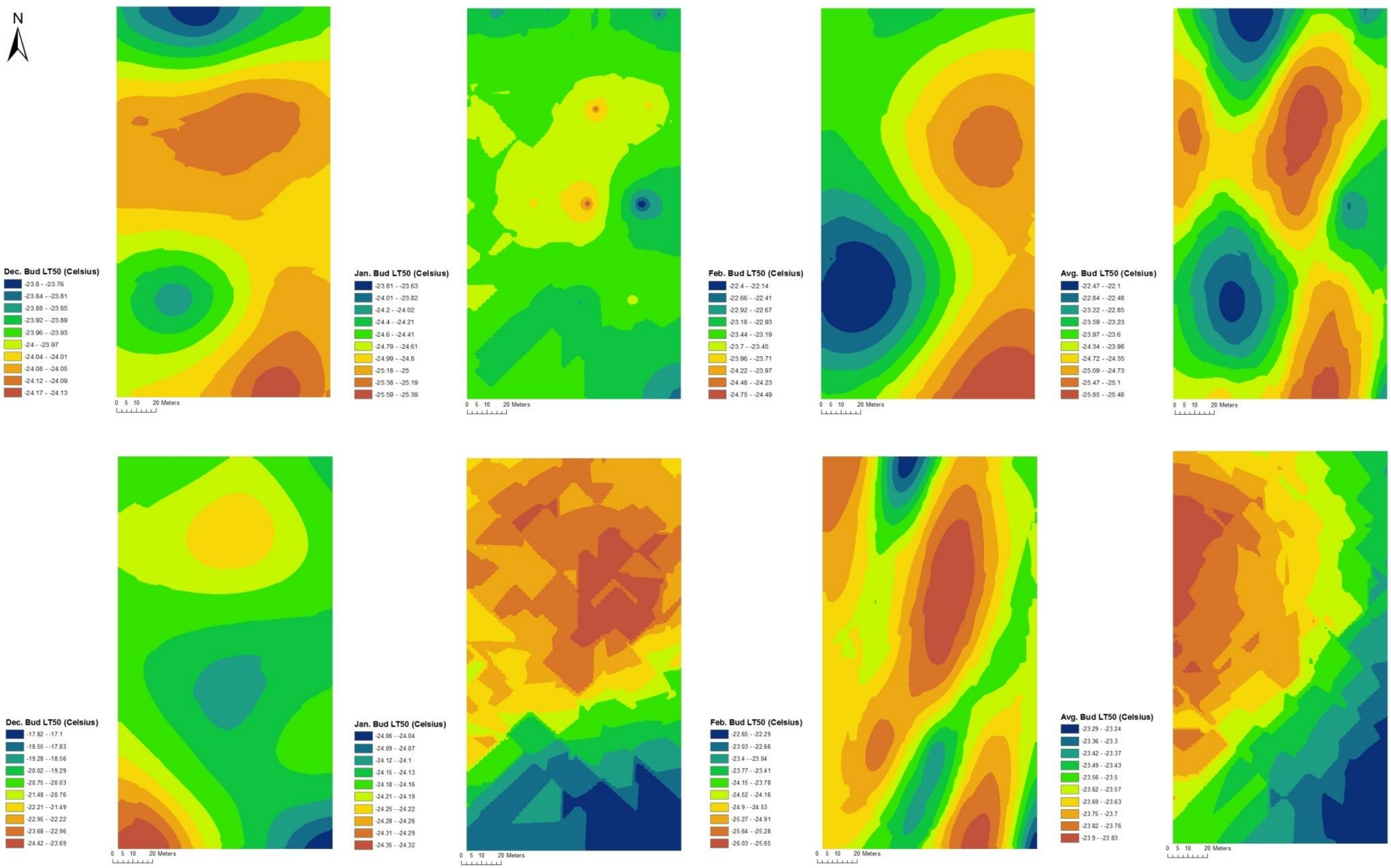

Figure 3.13 Maps of monthly and mean bud LT50 values for Cave Spring Riesling in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT50. Bottom: 2011 maps for December, January, February, and mean bud LT50. Morans I results for 2010 mean bud LT_{50}: z-score = 0.5672 (random); Morans I results for 2011 mean bud LT_{50}: z-score = -1.2599 (random).

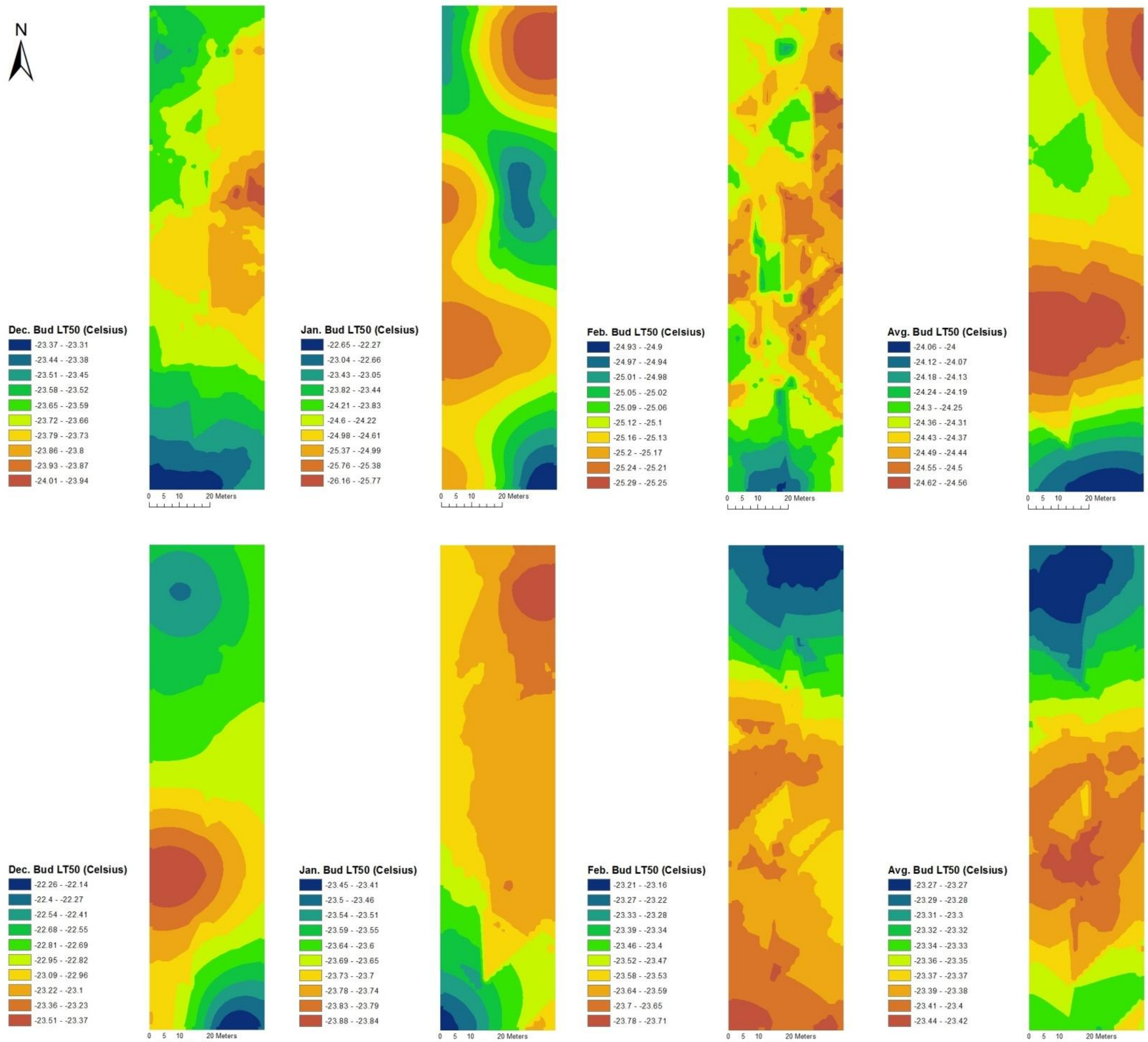

Figure 3.14 Maps of monthly and mean bud LT50 values for Lowrey Riesling in 2010 and 2011. Top: 2010 maps for December, January, February, and mean bud LT50. Bottom: 2011 maps for December, January, February, and mean bud LT50. Morans I results for 2010 mean bud LT_{50}: z-score = 0.7322 (random); Morans I results for 2011 mean bud LT_{50}: z-score = -1.4734 (random).

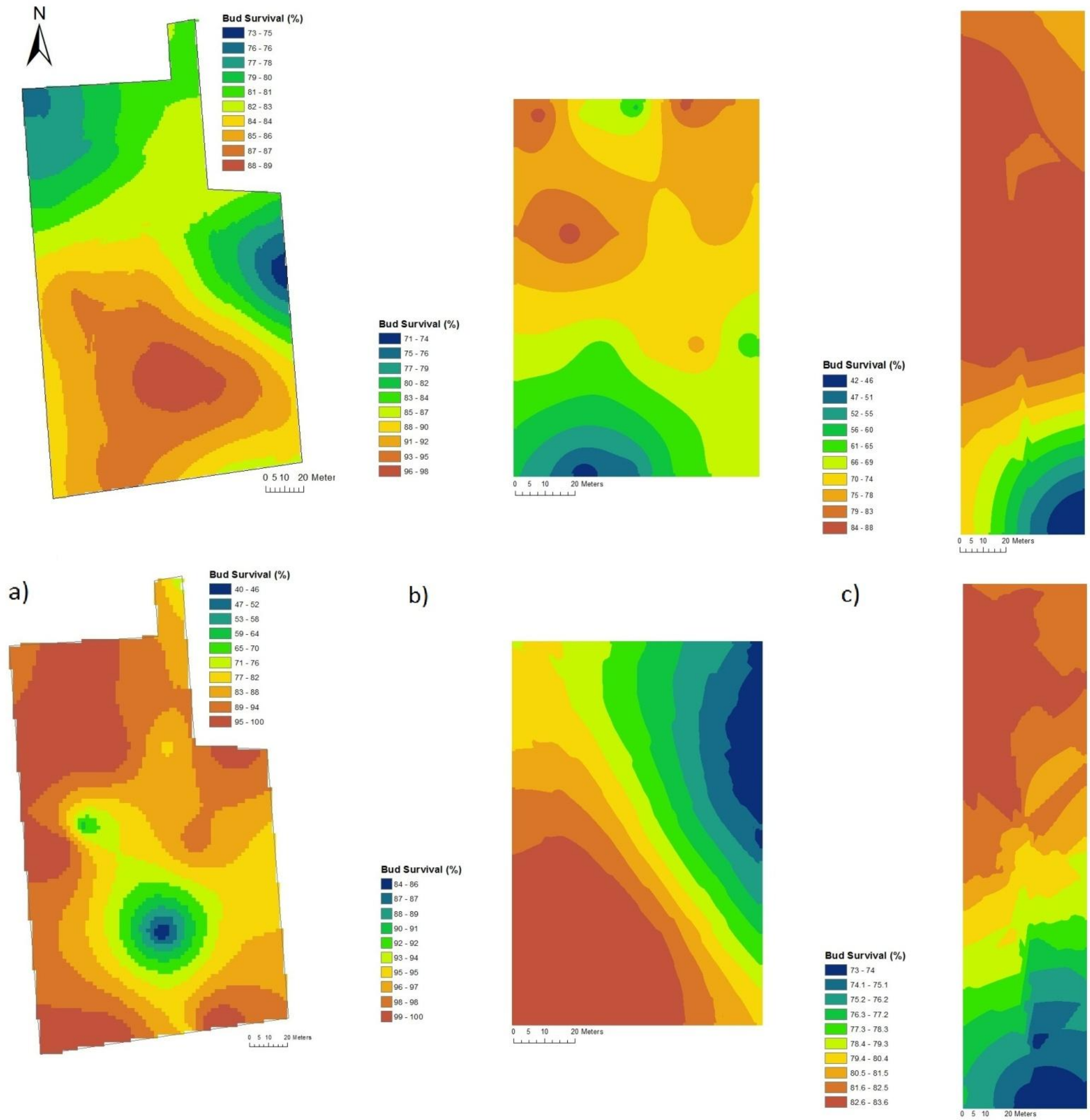

Figure 3.15 Maps of bud survival for Buis, George, and Hughes Riesling blocks in 2010 and 2011. a) Buis block, top 2010, bottom 2011; b) George block, top 2010, bottom 2011; c) Hughes block, top 2010, bottom 2011.

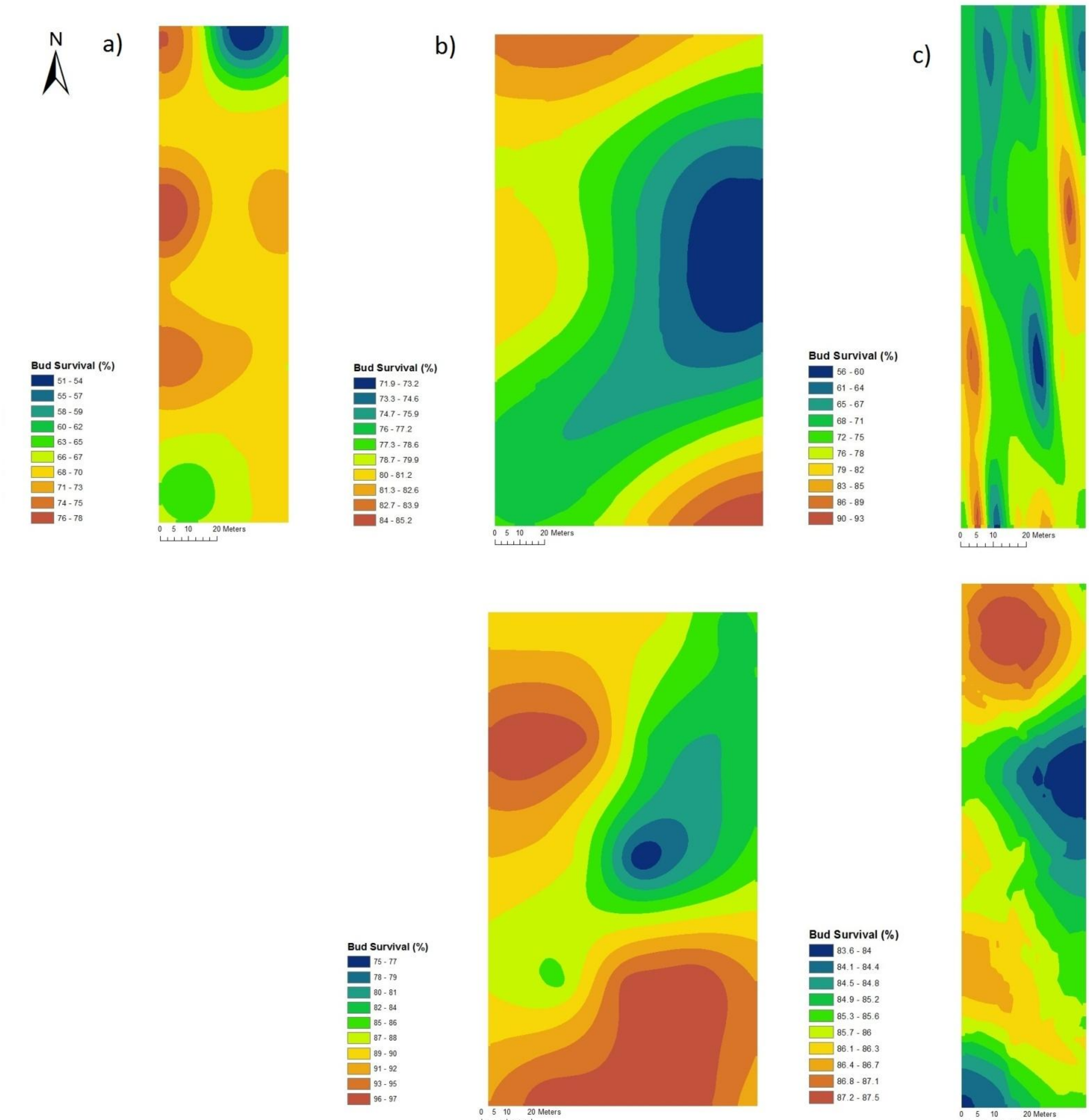

Figure 3.16 Maps of bud survival for Lambert, Cave Spring, and Lowrey Riesling blocks in 2010 and 2011. a) Lambert block, top 2010; b) Cave Spring block, top 2010, bottom 2011; c) Lowrey block, top 2010, bottom 2011.

Chapter 4: The *terroir* of Bud Hardiness – Relationships and Correlations

4.1 Introduction

Winter injury is a major concern in wine regions that experience cold temperatures during the winter months. It is associated with not just absolute temperature but also weather conditions and temperature fluctuations from late fall to early spring (Lisek 2007, Scagel et al. 2010, Zabadal et al. 2007). As such, it is one of the most limiting factors to plant growth and distribution in continental climates (Burke 1976). For grapevines the wintering bud is the most susceptible to winter injury (followed by the canes and trunk) with the fruiting bud, in particular, being the least resistant to damage (Edgerton and Shaulis 1953, Fennell 2004, Hamman et al. 1990, Howell et al. 1978, Schnabel and Wample 1987, Zabadal et al. 2007). Damage to fruiting buds can occur by extracellular or intracellular ice formation which causes anaerobic stress, dehydration, membrane destruction, and splitting and shearing of important adjacent tissues such as bark, xylem and phloem (Burke et al. 1976, Fennell 2004, Fitter and Hay 2002, Mills et al 2006, Purves et al. 2003).

Grapevines can prevent winter freeze damage by becoming winter hardy after completing a process known as cold acclimation. To become winter hardy, grapevines decrease water content, increase concentration of sugars and unsaturated fatty acids, and develop periderm (Ashworth et al. 1993, Burke et al. 1976, Fennell 2004, Gusta et al. 2005, Keller 2010, Mullins et al. 1996, Sauter et al. 1996, Xin and Browse 2000, Zabadal et al. 2007). Grapevine buds in particular undergo a process called supercooling which is aided by the accumulation of solutes and inhibits the formation of ice (Burke et al. 1976, Fitter and Hay 2002, Keller 2010, Wolfe and Bryant 1999, Zabadal et al. 2007). Maximum hardiness is achieved by mid-winter, once temperatures are consistently at or below -5^{o}C, and is maintained until March (Basinger and Hellman 2006, Keller 2010, Wolf and Cook 1992, Zabadal et al. 2007). The level of hardiness achieved varies between cultivars, with the buds of most commercial cultivars surviving temperatures between -11 ^{o}C to -24 ^{o}C in cool climate regions (Badulescu and Ernst 2006, Mills et al. 2006, Wolf and Cook 1994). To measure bud hardiness, a method known as thermal analysis is often used (Burke et al. 1976, Zabadal et al. 2007). Buds are excised and placed in programmable freezers that drop temperatures at ≈ 3 to 4^{o}C per hour until a set minimum temperature is achieved (Basinger and Hellman 2006, Mills et al. 2006, Wolf and Cook 1992). Upon reaching a critical temperature, bud death occurs, producing high temperature exotherms (HTE, cause by extracellular ice) and low temperature exotherms (LTE, caused by intracellular ice; Badulescu and Ernst 2006, Fennell 2004).The lower the temperature at which LTE peaks occur, the more winter hardy the buds.

One of the factors which may strongly affect the initiation and extent of cold acclimation is water availability and use. Water availability is often measured as soil moisture percentage and has been found to be strongly correlated with water use and growth of grapevines (Mullins et al. 1996, Sivilotti et al. 2005, van Leeuwen and Seguin 2006, Williams and Araujo 2002). The extent to which a vine uses water is known as its vine water status and is influenced by climate, soil, and vine management (Taylor et al. 2010, van Leeuwen and Seguin 2006). Vine water status is numerically represented by the leaf ψ of the vine, which decreases from root to apical tip and is the sum of the solute and pressure potentials (Purves et al. 2003). Under natural conditions, the leaf ψ of vines can vary spatially within a vineyard since root depth, soil water retention, evapotranspiration rates, and sun exposure can all affect water status (Koundouras et al. 2006, Taylor et al. 2010). When soil moisture and leaf ψ are low, grapevines enter a state of water stress; grapevines are one of the few woody plants that perform well in these conditions (Acevedo-Opazo et al. 2010, Koundouras et al. 2006, Sivilotti et al. 2005, van Leeuwen and Seguin, 2006). Water stress can accelerate the ripening of berries, lower yields, and increase wine aromas and flavours (Koundouras et al. 2006, van Leeuwen and Seguin 2006). Water stress has also been found to promote growth cessation and cold acclimation (Basinger and Hellman 2006, Gillerman et al. 2006, Koundouras et al. 2006). Other factors can also affect cold acclimation and hardiness including yield, vine size, and nutrients. For example, low yielding vines can have greater freeze tolerance; larger vines can mature more slowly, making them more prone to winter injury (Clore et al. 1974, Fennell 2004, Howell et al. 1978, Lisek, 2007, Zabadal et al. 2007); and higher nitrogen levels at harvest can increase vegetative growth and water demands, and decrease cold tolerance (Scagel et al. 2010).

As previously stated, winter injury is a concern for cool climate wine regions in Northern latitudes. This includes the Niagara Peninsula which receives approximately 1400 growing degree days and grows cold hardy *Vitis vinifera* cultivars such as Riesling, Gewurztraminer, Pinot noir, and Cabernet franc (Clore et al. 1974, van Leeuwen and Seguin 2006, Wine Council of Ontario 2011). The *terroir* of a region encompasses environmental characteristics (such as mesoclimate) as well as vine biology (such as cultivar; Reynolds et al. 2007, van Leeuwen and Seguin 2006). To learn more about the *terroir* of a region, GIS is becoming an increasingly important tool since it allows for mapping study areas with high spatial resolution and accuracy, both of which are needed for deducing spatial patterns of vineyard characteristics (Morari et al. 2009, Vaudour 2002). GIS is more effective when used with multivariate statistics. This includes the use of data-clustering and principal components analysis (Acevedo-Opazo et al. 2008, Acevedo-Opazo et al. 2010, Bramley et al. 2011, Bramley and Hamilton 2004, Morari et al. 2009, Reynolds et al. 2007).

To date, no GIS techniques have been applied for studying the *terroir* of winter hardiness. Spatial relationships between winter hardiness and other important *terroir* factors such as soil moisture, leaf ψ, yield, and fruit composition are still unknown. By using thermal analysis, and statistical and GIS methods, these spatial relationships were investigated for Cabernet franc and Riesling vineyards in the Niagara region to help define areas of elevated hardiness (low bud LT_{50} values) and low hardiness (high bud LT_{50} values). It was hypothesized that since past literature has reported that water stress promotes cold acclimation, soil moisture and leaf ψ would be spatially correlated to bud LT_{50} values. In addition, further relationships between LT_{50} values and yield components, fruit composition, and vine size would be demonstrated, aiding growers in anticipating the occurrence of winter bud damage.

4.2 Materials and Methods

4.2.1 Field and Laboratory Procedures

Six commercial vineyard blocks of both Riesling and Cabernet franc were chosen for this project. The blocks were located in five of the ten sub-appellations of the Niagara Peninsula, including: Niagara Lakeshore, Four Mile Creek, St. David’s Bench, Lincoln

Lakeshore (north and south sections), and Beamsville Bench [Vintners' Quality Alliance (VQA) 2009]. The general features of each vineyard can be found in Table A1. Approximately 75 sentinel vines were chosen per block with a smaller subset of these vines being chosen for leaf ψ, bud LT_{50}, bud survival, and monoterpene analysis (15 to 24 vines). The vines selected were healthy, and were representative of the vines within the block. A Raven Invicta 115 GPS (Global Positioning System) Receiver, Raven Industries (Sioux Falls, SD) (with 1.0 to 1.4 m accuracy) was used to delineate the shape of each vineyard block and geolocate each sentinel vine. The coordinates from each block were imported ArcGIS [Environmental Systems Research Institute (ESRI), Redlands, CA]. Soil moisture and leaf ψ measurements, and harvest procedures were completed following the same procedures as Reynolds et al. (2010a). Laboratory analysis of Cabernet franc samples, including pH, Brix, TA, and phenolic analyte measurements, was completed using the same procedures as Hakimi Rezaei et al. (2006); laboratory analysis of Riesling samples, including pH, Brix, TA, and monoterpene measurements, followed the work of Reynolds et al. (2010a,b).

4.2.2 Statistics procedure

Statistical analysis of the data was performed using XLStat (2012 version, Addinsoft SARL, New York, NY). Each variable was first checked for normality and errors before completing any other procedures. Correlation tests were performed for i) correlations between water metrics, fruit composition, vine size, bud survival, and mean bud LT_{50}, and ii) correlations between water metrics, monthly and mean bud LT_{50}, vine size, and bud survival. K-means clustering analysis (with three clusters) was performed to prepare data for PCA. PCA was used to illustrate the interactions between large numbers of variables and was run using the cluster means. In all cases, 100% explained variability was achieved using two components.

In addition to analysing multivariate relations with PCA, multilinear regression was also used. Multilinear regression is a useful parametric test to perform when one wants to analyse multivariate relationships as they relate to a single dependent variable. Unlike PCA, however, multilinear regression requires normalized data by definition (Warner 2008). As such, if a block contained ≥ five non-normally distributed variables, efforts were made to normalize or eliminate these variables when needed. Normalization was most often simply a case of removing an outlier. This was justified if there was a strong possibility of Type I (false positive) error. For this study 'best model' linear regression has been chosen since it can run all combinations of variables and selects the model with the lowest error value. Numerous model runs were completed in a step-wise manner, with non-significant variables being removed from the model. Models were only accepted as reliable if they were significant ($p \leq 0.05$) and contained at least one significantly contributing variable. Temperature and precipitation data was obtained from Environment Canada at the Vineland Research Station.

4.2.3 GIS Mapping procedures

The GIS (geographic information system) program ArcGIS 10.1 [Environmental Systems Research Institute (ESRI), Redlands, CA] was used for all mapping procedures. Data were imported into ArcGIS from Microsoft Excel. Data were interpolated using the (simple) kriging method. The interpolations chosen had the lowest error values and had no bulleting or other irregular geometric patterns, where possible. All interpolations were classified with 10 equal intervals and were displayed to a 2-m resolution. Raster calculator was also used to display the spatial patterns of predicted mean bud LT_{50} values determined using model equations from the linear regression tests.

4.3 Results

Chapter 4 results focus on the berry, soil moisture, leaf ψ, and yield relationships of mean bud LT_{50} measurements. Three statistical methods were used to explore the relationships between mean bud LT_{50} and other berry and vine characteristics. Pearson's correlation tests were completed and the results are available in *Appendix I*. PCA was also completed for each block after clustering of the data (Figs. 4.1-4.12). The third statistical analysis completed was multilinear regression, where mean bud LT_{50} was the dependent variable. When the model was found to be significant, the equation, R^2, and RMSE (root mean square error) values are given. Tables 4.1 and 4.2 display the significance of the models and their relevant variables. The correlation test, PCA, and linear regression relationships found for mean bud LT_{50} were compared with the relationships found in PCAs and correlation tests for soil moisture, leaf ψ, and yield. These comparisons revealed secondary relationships between mean bud LT_{50} and soil moisture, leaf ψ, and yield and are described below along with direct relationships between mean bud LT_{50} and other variables. Secondary relationships were in agreement with direct relationships in all cases. Sites producing monthly bud LT_{50} anomalies, as described in *Chapter 3*, will also be addressed.

4.3.1 Cabernet franc

(*i) Buis*

In 2010, mean bud LT_{50} was negatively correlated with berry weight (*p*-value = 0.047). According the PCA diagram (Fig. 4.1), mean bud LT_{50} was negatively related to bud survival (as anticipated) and positively related to yield. It was also positively associated with vine size (negatively related to leaf ψ and positively related to yield in both PCA and correlation tests, Tables A2 and A3), berry weight, and TA (positively associated with yield). In the linear regressions results (Table 4.1, Fig. 4.13), vine size was a significant variable which was also correlated to yield (Table A3).

In 2011, PCA results (Fig. 4.1) show that mean bud LT_{50} was negatively related to yield, berry weight [positively related to soil moisture and yield (PCA and correlation tests, Table A3)], pH [positively related to soil moisture (PCA and correlation tests, Table A2) and yield], and vine size [negatively related to leaf ψ and positively related to yield (PCA and correlation tests, Table A3)]. The linear regression test produced significant results (Table 4.1, Fig. 4.13) where vine size was significant (also positively correlated with yield)

When comparing between years, it was found that mean bud LT_{50} was related to yield, berry weight, and vine size both years but that these relationships changed between years. Vine size was a variable in both linear regressions but was only significant in 2011. Primary and secondary relationships between mean bud LT_{50}, water metrics and yield revealed that, in 2010, mean bud LT_{50} was negatively related to soil moisture and leaf ψ, and positively related to yield. In 2011, mean bud LT_{50} was negatively related to soil moisture, positively related to leaf ψ, and negatively related to yield. In general, low mean bud LT_{50} was indicated by high soil moisture and low leaf ψ. No consistent relationships were found for yield.

(ii) George

In 2010, PCA results (Fig. 4.2) indicated that mean bud LT_{50} was negatively related to many variables including pH (positively linked with yield), Brix, phenolic analytes (positively related to leaf ψ), leaf ψ, bud survival, and yield. Of these variables, Brix, anthocyanins, colour, and bud survival were positively linked with soil moisture, leaf ψ, and yield. Also, when reviewing correlation results (Table A2, A3), anthocyanins and colour were negatively correlated with leaf ψ and yield ; Brix was negatively correlated with yield (Table 2.2 and Table 2.3). Linear regression of mean bud LT_{50} yielded significant results (Table 4.1, Fig. 4.14). Reviewing correlation results of the significant variables, berry weight was positively correlated with leaf ψ and yield, while anthocyanins were negatively correlated with the same two variables (Table 2.3).

In 2011, mean bud LT_{50} was positively correlated with bud survival, not as expected (*p*-value = 0.041). For PCA relationships (Fig. 4.2), mean bud LT_{50} was positively related to Brix, phenolic analytes, bud survival, and vine size. It was negatively related to pH, TA (positively related to leaf ψ in PCA, negative in correlation tests; also positively correlated with soil moisture), and leaf ψ. Of these variables, the PCA reveals that phenols and vine size were negatively related to soil moisture, leaf ψ, and yield, while pH was positively related to all three. Brix, anthocyanins, colour, and bud survival were negatively related to leaf ψ. Many of these relationships were supported by correlation tests (Table A2, A3). Linear regression also produced a significant model (Fig. 4.14) with bud survival, Brix (negatively correlated with soil moisture, leaf ψ, and yield), pH (negatively correlated with soil moisture), and anthocyanins (negatively correlated with leaf ψ) being significant variables (Table 4.1).

Primary and secondary relationships between mean bud LT_{50}, and water metrics and yield revealed that, in 2010, mean bud LT_{50} was negatively related to soil moisture and leaf ψ. In 2011, mean bud LT_{50} was negatively related to soil moisture, leaf ψ, and yield. In general, low mean bud LT_{50} was indicated by high soil moisture, high leaf ψ, and high yield.

(iii) Kocsis

The PCA results (Fig. 4.3) for Kocsis (2010) revealed that mean bud LT_{50} was negatively related to anthocyanins and colour (both positively correlated with soil moisture, Table A2). No similar PCA relationships were found for soil moisture, leaf ψ, or yield. No significant linear regression model was found in 2010. In 2011, mean bud LT_{50} was positively correlated with bud survival (*p*-value = 0.035). PCA results (Fig. 4.3) found that mean bud LT_{50} was negatively related to berry weight (positively related with soil moisture), TA, and vine size [negatively correlated with soil moisture, positively correlated with leaf ψ, positively associated with yield (both PCA and correlation results); Tables A2 and A3, and Fig. 4.3]. Linear regression yielded a significant model (Table 4.1, Fig. 4.15) where leaf ψ was a significant variable.

In 2010, primary and secondary characteristics revealed that mean bud LT_{50} was negatively related to soil moisture, with no definitive relationships for leaf ψ or yield. In 2011, mean bud LT_{50} was positively associated with leaf ψ and negatively associated with yield. No consistent trend for soil moisture was found. In general, low bud LT_{50} was indicated by high soil moisture, low leaf ψ, and high yield.

(iv) Lambert

In 2010, no berry composition data was available. PCA results showed that mean bud LT_{50} was positively related to both leaf ψ and bud survival (Fig. 4.4). Neither of these variables was related to soil moisture. No correlations were found when reviewing Table A2 and Table A3. Linear regression did not yield significant results. In 2011, PCA results revealed that mean bud LT_{50} was positively related to colour (Fig. 4.4). No similar PCA relationships or correlations were found for soil moisture, leaf ψ, or yield. Multilinear regression analysis produced a significant model (Table 4.1, Fig. 4.15) but only colour was significant. No PCA or linear regressions relationships were found to occur in both 2010 and 2011. No primary or secondary relationships between soil moisture, leaf ψ, or yield were found in 2010. In 2011, leaf ψ was positively related to mean bud LT_{50}.

(v) Cave Spring

The PCA results in 2010 revealed that mean bud LT_{50} was positively associated with yield, leaf ψ¸ vine size, and bud survival (all negatively linked with soil moisture, Fig. 4.5). It was also negatively associated with soil moisture, berry weight (negatively linked with leaf ψ in PCA, positively correlated to soil moisture in correlation tests), pH (negatively linked with leaf ψ), Brix (positively related to soil moisture), anthocyanins, and colour. Leaf ψ and yield had the same relationships as mean bud LT_{50} regarding Brix, anthocyanins, colour, vine size and bud survival, with most relationships appearing in correlation tests as well (Table A2, A3). A significant linear regression model was also achieved (Table 4.5, Fig. 4.16) where berry weight (positively correlated with soil moisture) was significant.

In 2011, PCA results (Fig. 4.5) indicated that mean bud LT_{50} was positively related to Brix and TA (both negatively correlated to yield, Table A3), and phenolic analytes (negatively related to yield in PCA, soil moisture in correlation tests, Table A2). Linear regression also yielded significant results (Table 4.1, Fig. 4.16) where berry weight (positively correlated with soil moisture) was significant.

For PCA results (Fig. 4.5) and linear regression (Table. 4.1) inconsistent relationships occurred for Brix, anthocyanins, colour, and berry weight. A review of the relationships between mean bud LT_{50} and soil moisture, leaf ψ, and yield in 2010 revealed that mean bud LT_{50} was negatively related to soil moisture, and positively related to both leaf ψ and yield. In 2011, no relationships were found for leaf ψ. However, mean bud LT_{50} was negatively related to both soil moisture and yield. In general, low mean bud LT_{50} was indicated by high soil moisture, low leaf ψ. No consistent trends were found for yield.

vi) Lowrey

In 2010, PCA results (Fig. 4.6) revealed that mean bud LT_{50} was positively associated with pH (negatively correlated to yield, Table A3), Brix (negatively associated/correlated with yield, positively associated and correlated with soil moisture, Table A2), TA (positively associated with soil moisture, negatively linked and correlated with yield, Table A3), and phenols (positively correlated to soil moisture, negatively correlated to yield, Tables A2 and A3). It was also negatively associated with yield (negatively correlated with leaf ψ, Table A2) and berry weight (negatively associated with soil moisture, positively correlated to yield). The linear regression yielded significant results (Table 4.1, Fig. 4.17) where berry weight (positively correlated to yield), anthocyanins (negatively correlated to yield), and soil moisture were all significant.

According to the PCA results in 2011 (Fig. 4.6), mean bud LT_{50} was negatively related to yield and soil moisture, and positively related to Brix, TA (negatively related to yield, positively correlated to leaf ψ, Table A2), and phenolic analytes. Phenols were negatively related to soil moisture. Brix and phenolic analytes were negatively related to yield in both PCA and correlation tests (Fig. 4.6, Table A3). Multilinear regression also produced significant results (Table 4.1, Fig. 4.17) where TA (positively correlated with leaf ψ) and berry weight (positively correlated with yield) were significant.

When comparing 2010 and 2011, it was found that mean bud LT_{50} was negatively related to yield and positively related to Brix, TA, and phenolic analytes for both years. Additionally, Brix was a significant variable for both linear regression models. In 2010, primary and secondary characteristics revealed that mean bud LT_{50} was positively related to soil moisture and leaf ψ, and negatively related to yield. In 2011, mean bud LT_{50} was negatively related to soil moisture and yield, and positively related to leaf ψ. In general, low mean bud LT_{50} was indicated by low soil moisture, low leaf ψ, and high yield.

(vii) General Patterns

For the Lakeshore blocks (Lambert, George), mean bud LT_{50} was negatively associated with soil moisture, leaf ψ, and yield. In the Plains blocks (Buis, Kocsis), mean bud LT_{50} was negatively associated with soil moisture and positively associated with leaf ψ. No consistent association was found with yield. For the Escarpment blocks (Cave Spring, Lowrey), mean bud LT_{50} was negatively linked with soil moisture, positively linked with leaf ψ, and negatively linked with yield. In general, low mean bud LT_{50} was indicated by high soil moisture, low leaf ψ, and high yield. Sixty-seven percent of the variables found with linear regression could be explained by leaf ψ, soil moisture, and yield with multiple blocks identifying berry weight as significant. This suggests that leaf ψ, soil moisture, and yield are related to mean bud LT_{50} and that berry weight may be an important indicator of winter hardiness.

4.3.2 Riesling

(i) Buis

According to the PCA results (Fig. 4.7), in 2010 mean bud LT_{50} was positively related to yield and leaf ψ, and negatively related to bud survival and Brix (both of which were also negatively associated with leaf ψ). When reviewing correlation results, Brix was negatively related to yield (Table A3). No significant model was produced using linear regression. In 2011, PCA results (Fig. 4.7) revealed that mean bud LT_{50} was positively related to soil moisture, leaf ψ, yield, berry weight, and TA. It was also negatively associated with bud survival and pH (positively correlated to soil moisture, Table A4). Linear regression produced a significant model (Table 4.2, Fig. 4.18) where Brix (negatively correlated to yield) was significant.

When comparing 2010 and 2011, it was found that mean bud LT_{50} had the same relationships with yield (positive), leaf ψ (positive), and bud survival (negative). No relationships with soil moisture were determined in 2010. However, in 2011, mean bud LT_{50} was positively related to soil moisture. In general, low mean bud LT_{50} was indicated by low soil moisture, low leaf ψ, and low yield.

(ii) George

According to PCA results (Fig. 4.8), in 2010 mean bud LT_{50} was positively related to soil moisture (positively correlated with leaf ψ, Table A4) and Brix (positively associated with soil moisture, negatively associated/correlated with yield), and negatively related to yield and vine size (negatively associated with yield, positively associated with leaf ψ). In contrast to PCA results, correlation results indicated that vine size was positively correlated with yield (Table A5). Significant linear regression results were also produced (Table 4.2, Fig. 4.19), where monoterpenes (negatively correlated to leaf ψ) were significant.

In 2011, mean bud LT_{50} was positively correlated with bud survival (*p*-value = 0.011). Mean bud LT_{50} was negatively related to soil moisture (positively correlated with yield, Table A4) in the PCA results (Fig. 4.8). No PCA relationships for leaf ψ or yield were found. Linear regression produced significant results (Table 4.2, Fig. 4.19) with TA (negatively correlated with soil moisture and positively correlated with leaf ψ), leaf ψ, and bud survival being significant variables.

Comparing 2010 and 2011, it was found that mean bud LT_{50} was positively related to soil moisture in 2010 and negatively related to it in 2011. No similar variables were found when comparing regression results. In 2010, primary and secondary characteristics revealed that mean bud LT_{50} was positively related to soil moisture and negatively related to leaf ψ and yield. In 2011, mean bud LT_{50} was negatively related to soil moisture and yield, and positively related to leaf ψ. In general, low mean bud LT_{50} was indicated by high yield. No consistent relationships were found for soil moisture or leaf ψ.

(iii) Hughes

In 2010, PCA results (Fig. 4.9) indicated that mean bud LT_{50} was positively associated with yield and monoterpenes. No relationships between soil moisture, leaf ψ, or yield were found for these variables. Correlation results did not provide any further relationships (Table A4 and Table A5). A significant multilinear regression model was produced in 2010 (Table 4.2, Fig. 4.18) with berry weight (positively correlated with both leaf ψ and yield) being a significant variable.

In 2011, PCA results (Fig. 4.9) revealed that mean bud LT_{50} was positively related to leaf ψ, and yield, berry weight, pH, and vine size. It was also negatively related to soil moisture, bud survival, Brix, TA (positively correlated with yield, Table A5), and monoterpenes. Soil moisture and leaf ψ were also related to these variables, with the exception of vine size. Yield shared similar relationships to mean bud LT_{50} with the exception of Brix. According to the correlation results, leaf ψ was positively correlated with soil moisture and berry weight, and negatively correlated with monoterpenes. No significant linear regression model was produced for this year.

Comparing PCA results from 2010 and 2011, it was found that mean bud LT_{50} was positively related to yield for both years. In 2010, primary and secondary characteristics revealed that mean bud LT_{50} was positively related to leaf ψ and yield. No relationships were found for soil moisture. In 2011, mean bud LT_{50} was negatively related to soil moisture and positively related to leaf ψ. No definitive relationship was found for yield. In general, low mean bud LT_{50} was indicated by high soil moisture, low leaf ψ, and low yield.

(iv) Lambert

PCA results from 2010 (Fig. 4.10) revealed that mean bud LT_{50} was negatively related to soil moisture. It was also negatively related to berry weight, pH, and vine size (all positively associated with soil moisture, negatively associated with yield). It was also positively related to yield and TA. No relationships were found for leaf ψ. For correlation results, berry weight was positively correlated with leaf ψ, and pH was negatively correlated with yield (Table A4 and Table A5). Linear regression yielded no significant results. In 2011, PCA results showed that mean bud LT_{50} was positively related to soil moisture and TA (positively associated with soil moisture, positively correlated with leaf ψ, Table A4), and negatively related to yield (Fig. 4.10). No further relationships were found for leaf ψ or yield. Linear regression yielded no significant results.

In 2010 and 2011, according to PCA results, soil moisture and yield were related to mean bud LT_{50} (Fig. 4.10). However, these relationships were not consistent between years. No significant linear regression results were found for either year. In 2010, primary and secondary characteristics revealed that mean bud LT_{50} was negatively related to soil moisture and leaf ψ, and positively related to yield. In 2011, mean bud LT_{50} was positively related to soil moisture and leaf ψ, and negatively related to yield. Since opposite patterns of low bud LT_{50} occurred between years, no general statement can be made.

(v) Cave Spring

In 2010, according to PCA results (Fig. 4.11), mean bud LT_{50} was negatively related to Brix (positively associated with soil moisture and yield, negatively associated with leaf ψ) and monoterpenes, and positively related to TA (negatively associated with soil moisture and yield, positively associated with leaf ψ). No correlations were found between these variables and soil moisture, leaf ψ, or yield. The linear regression produced significant results (Table 4.2, Fig. 4.20), with TA as a significant variable. No correlation results corroborated with the linear regression results.

In 2011, mean bud LT_{50} was positively correlated with berry weight and leaf ψ (*p*-values of 0.005 and 0.042, respectively). PCA results (Fig. 4.11) found that mean bud LT_{50} was positively related to soil moisture and yield, berry weight and monoterpenes (both positively associated with yield), and vine size (positively related to soil moisture, yield). It was also negatively related to bud survival (negatively related to soil moisture, yield). No significant model was produced using linear regression.

Comparing 2010 and 2011, no consistent relationships were found for PCA, correlation tests, or linear regression. In 2010, primary and secondary characteristics revealed that mean bud LT_{50} was negatively related to soil moisture and yield but positively related to leaf ψ. In 2011, mean bud LT_{50} was positively associated with soil moisture, leaf ψ¸ and yield. Opposite relationships with mean bud LT_{50} occurred between years for soil moisture and yield. However, low bud LT_{50} was related to low leaf ψ.

(vi) Lowrey

In 2010, PCA results (Fig. 4.12) indicated that mean bud LT_{50} was negatively related to soil moisture, yield, berry weight, pH, Brix, monoterpenes, and vine size (positively correlated with yield, Table A5). It was positively related to bud survival (negatively related to leaf ψ). Soil moisture and yield had opposite trends compared to mean bud LT_{50} for all variables listed. Berry weight, pH, and soil moisture were positively related to leaf ψ. Linear regression yielded significant results in 2010 (Table 4.2 and Fig. 4.21) where vine size (positively correlated with yield) was a significant variable.

In 2011, PCA results (Fig. 4.12) found that mean bud LT_{50} was positively related to soil moisture, leaf ψ, and TA (positively related to yield in both PCA and correlation tests, Table. A5). It was negatively related to Brix (negatively associated with soil moisture, leaf ψ). A significant model was produced using linear regression (Table 4.2, Fig. 4.21). Correlation tests revealed no additional relationships.

Comparing linear regression results for 2010 and 2011, soil moisture and leaf ψ appeared in both years. However, they were non-significant in 2010. In 2010, primary and secondary characteristics revealed that mean bud LT_{50} was negatively related to soil moisture and yield. Leaf water potential showed inconsistent relationships. In 2011, mean bud LT_{50} was positively associated with soil moisture, leaf ψ¸ and yield. In general, low mean bud LT_{50} was indicated by low soil moisture and high leaf ψ. No consistent results were found for yield. Opposite patterns between mean bud LT_{50} and soil moisture, leaf ψ and yield occurred between years.

(vii) General patterns

For the Lakeshore blocks (Buis, George) and Plains blocks (Hughes, Lambert), mean bud LT_{50} was positively associated with soil moisture, leaf ψ, and yield. For the Escarpment blocks (Cave Spring, Lowrey), mean bud LT_{50} was positively linked with soil moisture, negatively linked with leaf ψ, and positively linked with yield. For Riesling blocks in general, low mean bud LT_{50} was indicated by low soil moisture, leaf ψ, and yield. Fifty-five percent of variables found with linear regression could be explained with soil moisture, leaf ψ, and yield. This suggests that leaf ψ, soil moisture, and yield are related to mean bud LT_{50}.

4.3.3 Anomalies

As first described in *Chapter 3*, five study sites showed monthly deviations from mean bud LT_{50} values. These sites include three Cabernet franc blocks [George (2011), Kocsis (2010), and Lowrey (2011)] and two Riesling blocks [George (2011) and Hughes (2011)]. With the exception of Hughes Riesling (2011), the December monthly values were unrelated to mean bud $LT_{50.}$ For George Cabernet franc (2011), PCA results (Fig. A21) found that December bud LT_{50} values were negatively related to mean bud LT_{50} values and bud survival. They were positively related to leaf ψ. For Kocsis Cabernet franc (2010), PCA results (Fig. A21) found that December bud LT_{50} was positively related to leaf ψ. For Lowrey Cabernet franc (2011), the PCA results (Fig. A21) revealed that December bud LT_{50} values were positively related to leaf ψ. No relationships with mean bud LT_{50} were found. A significant model was produced using linear regression ($Pr > F = 0.006$) with yield (positive) as a significant variable. For George Riesling (2011), no significant relationships regarding soil moisture, leaf ψ, yield, or mean bud LT_{50} were found. For Hughes Riesling (2011), PCA results (Fig. A21) indicated that January bud LT_{50} was negatively related to leaf ψ and mean bud $LT_{50.}$ Significant results were produced using linear regression ($Pr > F = 0.007$), with bud survival (negative) as one of the significant variables. In summary, for each anomaly block PCA was run for, leaf ψ was related to December/January bud LT_{50} measurements. Most blocks did not show relationships with mean bud LT_{50}. All blocks yielded significant linear regression results, with soil moisture, yield, and bud survival being significant variables for some models.

4.4 Discussion

The purpose of this part of the study was to investigate suspected relationships between mean bud LT_{50} and other variables within the vineyard, such as soil moisture, leaf ψ, yield, and berry composition. Previous studies within this thesis have concluded that soil moisture, leaf ψ, and yield were related to berry composition variables (*Chapter 2*). The relationships for soil moisture were the least consistent; however, leaf ψ and yield were often positively related to berry weight and TA, and negatively related to Brix, pH, and phenolic analytes. Further research revealed that spatial patterns of soil moisture, leaf ψ, yield, and bud LT_{50} were temporally stable over the two year period when assessed visually (*Chapter 3*). In this study, past research which indicated a causal relationship between water metrics and vine acclimation (Basinger and Hellman 2006, Gillerman et al. 2006, Koundouras et al. 2006) was supported. It was found that mean bud LT_{50} had direct relationships to water metrics and yield, and indirect relationships to these variables through berry composition.

For Cabernet franc in 2010, greater hardiness (lower mean bud LT_{50}) was indicated by higher soil moisture, higher leaf ψ, and lower yield. However, relationships regarding leaf ψ and yield were somewhat inconsistent. Relationships with these variables were much more pronounced in 2011, with greater hardiness being promoted by high soil moisture, low leaf ψ, and high yield. These results support the findings of *Chapter 3* which suggested that yield and leaf ψ were less temporally stable than soil moisture. Therefore, the hardiness of Cabernet franc buds was generally promoted by high soil moisture, low leaf ψ, and high yield. In *Chapter 2* it was noted that leaf ψ and yield were positively related to one another concerning berry composition variables. However, this was not the case regarding mean bud LT_{50} patterns. Further investigations into this phenomenon showed that discrepancies between leaf ψ and yield, and mean bud LT_{50} patterns were often caused by vine size, a variable which showed inconsistent relationships in statistical analyses. If taken on berry composition variables alone (such as berry weight, Brix, and phenolic analytes, which appeared often in mean bud LT_{50} relationships), leaf ψ and yield were still positively related to one another. Inconsistent relationships with vine size and mean bud LT_{50} have been found when comparing other papers (Hamman et al. 1990, Wolpert and Howell 1984). In general, the promotion of bud hardiness by high soil moisture, low leaf ψ, and high yield supports the notion that well-balanced vines supplied with adequate water are hardier than under-cropped vines with limited soil moisture, or over-vigorous vines (Fennell 2004, Howell et al. 1978).

Differences in the location of vineyard blocks changed the relationships between mean bud $LT_{50,}$ water metrics and yield for the Cabernet franc blocks. Bud hardiness at the "Lakeshore" blocks (Lambert and George) was indicated by high soil moisture, high leaf ψ, and high yield; bud hardiness at "Plains" blocks (Buis and Kocsis) was promoted by low soil moisture, low leaf ψ, and both high and low yield; bud hardiness at "Escarpment" blocks (Cave Spring and Lowrey) was indicated by high soil moisture, low leaf ψ, and high yield. Varying mean bud LT_{50} relationships can possibly be explained by differences in climate and soil. The "Lakeshore" blocks lie on fine sandy or clay loam till with imperfect to poor drainage (Table A1; Shaw 2005). This area also receives the most temperate weather, with temperatures being moderated by the lake (Schlosser et al. 2005, Hakimi Rezaei and Reynolds 2010, Shaw 2005). Therefore, vines tend to be more vigorous with greater crop load, requiring high soil moisture, leaf ψ, and yield to remain balanced. The "Plains" blocks receive the most heat units during the summer and lie on soils with higher percentages of clay (Hakimi Rezaei and Reynolds 2010, Schlosser et al. 2005). As such, they require less soil moisture, but tend to experience greater water stress. These blocks may exemplify results found in other studies that suggest bud hardiness may benefit from water stress (Basinger and Hellman 2006, Gillerman et al. 2006). "Escarpment" blocks lie on silty clay and clay loam till, with weather patterns and drainage being affected by the escarpment (Hakimi Rezaei and Reynolds 2010, Schlosser et al. 2010). Thus, as with "Lakeshore" blocks, their bud hardiness was promoted by high soil moisture, and high yield, but also low leaf ψ.

In both 2010 and 2011, greater hardiness (lower mean bud LT_{50}) for Riesling buds was indicated by low soil moisture, low leaf ψ, and low yield. Opposing annual trends were observed for some blocks, especially with regards to yield. As mentioned in

Chapter 3, all vineyard blocks recorded higher yields in 2011 (positive relationships with mean bud LT_{50} for Buis, Cave Spring, and Lowrey) as compared to 2010 (negative relationships with these blocks). However, in general, lower yields were related to greater hardiness. As with berry composition relationships regarding berry weight, Brix, pH, and TA (*Chapter 2*), leaf ψ and yield were positively related to one another. Additionally, further results from *Chapter 2* supported findings in this study that suggested soil moisture was the least consistent variable regarding bud LT_{50} relationships. In many cases (George 2011, Hughes 2011, Lambert 2010, Cave Spring 2010, Lowrey 2010), soil moisture exhibited negative relationships with bud LT_{50}, suggesting that high soil moisture (related to higher Brix, pH, and monoterpenes) was linked with greater hardiness. Therefore, while the effects of leaf ψ and yield on winter hardiness were strongly supported by the results, soil moisture was again more inconsistent. Past literature agrees with findings in this paper that lower crop loads and moderate water stress increase hardiness in white varieties (Fennell 2004, Howell et al. 1978, Gillerman et al. 2006, Lisek 2007). Furthermore, Gillerman et al. (2006) suggest that water deficits are more important towards the end of the growing season in order to promote cold acclimation and dormancy. For Riesling, the location of vineyard blocks did not change the relationships between mean bud LT_{50}, water metrics, and yield to the same extent as Cabernet franc. Bud hardiness at “Lakeshore” (Buis and George) and “Plains” (Hughes and Lambert) blocks were promoted by low soil moisture, low leaf ψ, and low yield. Bud hardiness at “Escarpment” blocks (Cave Spring and Lowrey) was indicated by high soil moisture, low leaf ψ, and low yield. It is suspected that Cave Spring and Lowrey displayed different trends from the other blocks with regards to soil moisture due to the effect of greater water drainage (Hakimi Rezaei and Reynolds 2010, Schlosser et al. 2010, Shaw 2005). Thus, as with Cabernet franc, the vines on the escarpment benefit from higher soil moisture due to increased water drainage as compared to other areas.

In a few cases for both Cabernet franc and Riesling, some monthly bud LT_{50} measurements were not correlated with mean bud LT_{50} values. Investigations into these relationships showed that the month of December was of greatest exception. This month marks the beginning of winter, where vines are actively acclimating to the cold. As such, they are still strongly influenced by the amount of water stress they experienced during the growing season. This is reflected in the results by the numerous relationships between December bud LT50 and leaf ψ. However, each of the linear regressions still reveals similar relationships to those of the mean bud LT_{50} results. This agrees with research done by Basinger and Hellman (2006) who found that water deficits regimes had marked differences on cold hardiness at the beginning of the dormant season (November/December), becoming less noticeable as the winter season continued on.

Previous work by Wolf and Cook (1994) showed that thermal analysis trials on grapevine buds provided a close approximation for bud survival in the field. As such, many methods have combined thermal analysis and survival trials (Howell et al. 1978, Howell and Shaulis 1980, Mills et al. 2006, Wolpert and Howell 1984). In this study, very few blocks showed direct correlations or linear regression relationships between bud survival and mean bud $LT_{50.}$ When they did occur, it was only in the 2011/2012 winter season. For Cabernet franc buds, these relationships were positive, suggesting that low bud LT_{50} values also led to low bud survival percentages. The opposite was true for Riesling where, using linear regression in particular, lower bud LT_{50} values were associated with greater bud survival. To explain these phenomena, it must be understood that once the critical bud LT_{50} temperatures are reached, buds (regardless of their hardiness compared to that of neighbouring vines) suffer necrosis. Therefore, to observe direct correlations between bud LT_{50} and bud survival, both analyses should be completed at the same time or after a cold snap as with past studies (Mills et al. 2006, Wolf and Cook 1994). As suggested first in *Chapter 3*, cultivar differences may drive this relationship. In *Chapter 3*, Cabernet franc was found to reach maximum hardiness earlier and to suffer less bud damage over the winter season, while Riesling was slower to acclimate and displayed much lower bud survival rates in 2010/2011 as compared to 2011/2012. Therefore, for Cabernet franc blocks, which were fairly uniform regarding bud LT_{50} values, vines located in cold pockets would have the greatest hardiness but would also be subjected to lowest temperatures, thus producing a positive relationship. For Riesling blocks, bud LT_{50} values were more varied, with negative relationship occurring between bud LT_{50} and bud survival. Therefore, as expected, less hardy buds were much more likely to experience damage than their hardier counterparts. However, as with the study by Wolf and Cook (1994), temperature should be monitored to allow for proper comparison between mean bud LT_{50} values and bud survival measurements. This is recommended for future bud hardiness studies as temperature, in concert with other vineyard characteristics, is important to bud hardiness and survival within a vineyard.

While many studies have made use of correlation tests (Reynolds et al. 2010a, Reynolds et al. 2010b, Reynolds et al. 2007), PCA relationships (Acevedo-Opazo et al. 2008, Acevedo-Opazo et al. 2010, Reynolds et al. 2010a, Reynolds et al. 2010b, Schlosser et al. 2005), and GIS (Bramley 2010, Bramley and Hamilton 2004, Bramley et al. 2011, Morari et al. 2009, Reynolds et al. 2010a, Reynolds et al. 2010b, Reynolds et al. 2007) to elucidate *terroir* patterns, linear regression has not been frequently used. In this study, it was found that linear regression successfully predicted bud LT_{50} values, with 10/12 Cabernet franc and 7/12 Riesling investigations yielding significant results. These frequently agreed with both PCA and correlation tests. When interpolated and compared to mean bud LT_{50} maps (Fig. 4.13 to Fig. 4.21), predicted bud LT_{50} values (using equations found in Tables 4.1 and 4.2) were visually similar to actual mean bud LT_{50} patterns. Strong examples of this can be seen in Fig. 4.13, Fig. 4.17, and Fig. 4.21. Multilinear regressions can now be run using GIS software. It is recommended that this avenue be investigated in the future in order to make this procedure even more robust.

4.5 Conclusions

In this study, it was hypothesized that relationships between mean bud LT_{50}, water metrics (soil moisture, leaf ψ), and yield would be found for both Cabernet franc and Riesling cultivars within the Niagara region. Correlation tests, PCA, multilinear regression, and GIS procedures were successfully used to support this hypothesis. Both direct and indirect relationships (using berry composition variables) with water metrics and yield were discovered. In general, Cabernet franc bud hardiness was promoted by high soil moisture, low leaf ψ, and high yield, with varying patterns occurring throughout the Niagara Region during the previous growing season. For Riesling, bud hardiness relationships were constant throughout the Peninsula, with low mean bud LT_{50} values being indicated by low soil moisture, leaf ψ, and yield. Further analysis revealed that monthly bud LT50 values were accurate representations of the average bud LT50s found in the majority of blocks suggesting that patterns of bud LT50 were stable over the winter months. However, exceptions did occur. In these cases, December bud LT_{50} was found to be closely linked with leaf ψ values using PCA, as during this month, all vines are actively acclimating to the cold and have not reached their full hardiness potential. Investigations into bud survival trends indicated, once again, that cultivar differences can affect bud hardiness and survival in continental climates.

4.6 Literature Cited

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4.7 List of Figures

Figure 4.4 Principal component analysis diagrams of the Lambert Cabernet franc vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

Figure 4.5 Principal component analysis diagrams of the Cave Spring Cabernet franc vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors. Phenol concentration relationships are not shown in a) since this variable was not analysed due to strong collinearity trends.

Figure 4.6 Principal component analysis diagrams of the Lowrey Cabernet franc vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

Figure 4.7 Principal component analysis diagrams of the Buis Riesling vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

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Figure 4.9 Principal component analysis diagrams of the Hughes Riesling vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

Figure 4.10 Principal component analysis diagrams of the Lambert Riesling vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

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Figure 4.12 Principal component analysis diagrams of the Lowrey Riesling vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

Supplemental Figures Relevant to this Chapter

Figure A22 Map of the Niagara wine region. Red circles represent Cabernet franc research blocks, green circles represent Riesling research blocks, and “+” represents the Vineland Research weather station. From left to right, Cabernet franc blocks are Cave Spring, Kocsis, George, Buis, Lambert, Lowrey; from left to right, Riesling blocks are Cave Spring, Hughes, George, Lambert, Buis, and Lowrey. Map courtesy of the Vintners Quality Alliance (VQA).

4.8 Tables and Figures

Table 4.1 Results of the linear regression tests for Cabernet franc vineyard blocks in 2010 and 2011. Models were considered significant if they had a *p*-value < 0.05 (95% confidence interval). RMSE is equal to degrees Celsius. Significance levels are defined as follows: * = p<0.05, ** = p<0.01, *** = p<0.001. Kocsis (2010) and Lambert (2010) did not produce significant models.

Block	Year	Equation (Avg. Bud LT_{50} =)	Significant variables (p-value < 0.05)	Adjusted R^2	RMSE
Buis	2010	-21.78 – 2.13 x (berry weight) + 1.50×10^{-3} x (vine size)	Berry weight	0.299 *	0.448
Buis	2011	-24.40 + 0.20 x (soil moisture) – 1.30×10^{-3} x (vine size)	Vine size	0.229 *	0.605
George	2010	-5.45 – 7.23 x (berry weight) – $1.12 * 10^{-2}$ x (anthocyanins)	Antho, Berry weight	0.481 *	0.671
George	2011	-50.31 – 0.45 x (Brix) + 9.71 x (pH) + 4.24 x 10^{-3} x (anthocyanins) + 2.59 x 10^{-2} x (bud survival)	Brix, pH, Antho Bud survival	0.598 *	0.449
Kocsis	2011	-16.62 – 4.11 x (berry weight) + 5.02 x 10^{-3} x (anthocyanins) + 0.36 x (soil moisture) + 0.45 x (leaf ψ)	Berry weight, Antho, Soil moisture, LWP	0.452 **	0.518
Lambert	2011	-29.47 + 0.18 x (colour) + 2.07 x (berry weight) + 1.52 x 10^{-2} x (bud survival)	Colour	0.336 **	0.493
Cave Spring	2010	-3.48 – 6.2 x (berry weight) + 0.99 x (leaf ψ)	Berry weight LWP	0.454 *	0.882
Cave Spring	2011	-38.94 + 0.44 x (yield) + 8.79 x (berry weight) + 3.96 x 10^{-2} x (bud survival)	Yield, Berry weight, Bud survival	0.483 *	0.515
Lowrey	2010	-44.41 + 7.94 x (berry weight) + 7.72 x 10^{-3} x (anthocyanins) +0.21 x (soil moisture)	Berry weight Antho Soil moisture	0.251 *	0.914
Lowrey	2011	-39.92 + 3.12 x (berry weight) + 2.30 x (TA)	Berry weight, TA	0.284 *	0.713

Table 4.2 Results of the linear regression tests for Riesling vineyard blocks in 2010 and 2011. Models were considered significant if they had a *p*-value < 0.05 (95% confidence interval). RMSE is equal to degrees Celsius. Significance levels are defined as follows: * = p<0.05, ** = p<0.01, *** = p<0.001. Buis (2010), Cave Spring (2011), Hughes (2011), and Lambert (2010, 2011) did not produce significant models.

Block	Year	Equation (Avg. Bud LT_{50} =)	Significant variables (p-value < 0.05)	Adjusted R^2	RMSE
Buis	2011	-18.57 + 3.45 x (berry weight) – 0.54 x (Brix)	Berry weight Brix	0.540 ***	0.568
George	2010	-30.59 +1.24 x (berry weight) + 0.44 x (monoterpenes) + 0.16 x (soil moisture)	Terpene Soil moisture	0.474 *	0.214
George	2011	-17.70 – 0.59 x (TA) + 0.35 x (leaf ψ) + 3.91 x 10^{-2} x (bud survival)	TA, LWP Bud survival	0.363 *	0.571
Hughes	2010	-3.45 – 0.43 x (yield) + 1.46 x (berry weight) – 6.40 x (pH)	Yield, Berry weight, pH	0.460 *	0.495
Cave Spring	2010	-25.21 – 2.88 x (berry weight) + 0.62 x (TA)	TA	0.306 **	1.052
Lowrey	2010	-15.90 + 4.40 x (berry weight) – 0.27 x (soil moisture) + 0.80 x (leaf ψ) – 3.11 x (vine size)	Berry weight Vine size	0.245 *	0.956
Lowrey	2011	-50.06 – 0.43 x (Brix) + 9.30 x (pH) + 0.23 x (yield) – 0.15 x (soil moisture) – 0.61 x (leaf ψ)	Yield, pH Brix, Soil moisture, LWP	0.481 **	0.520

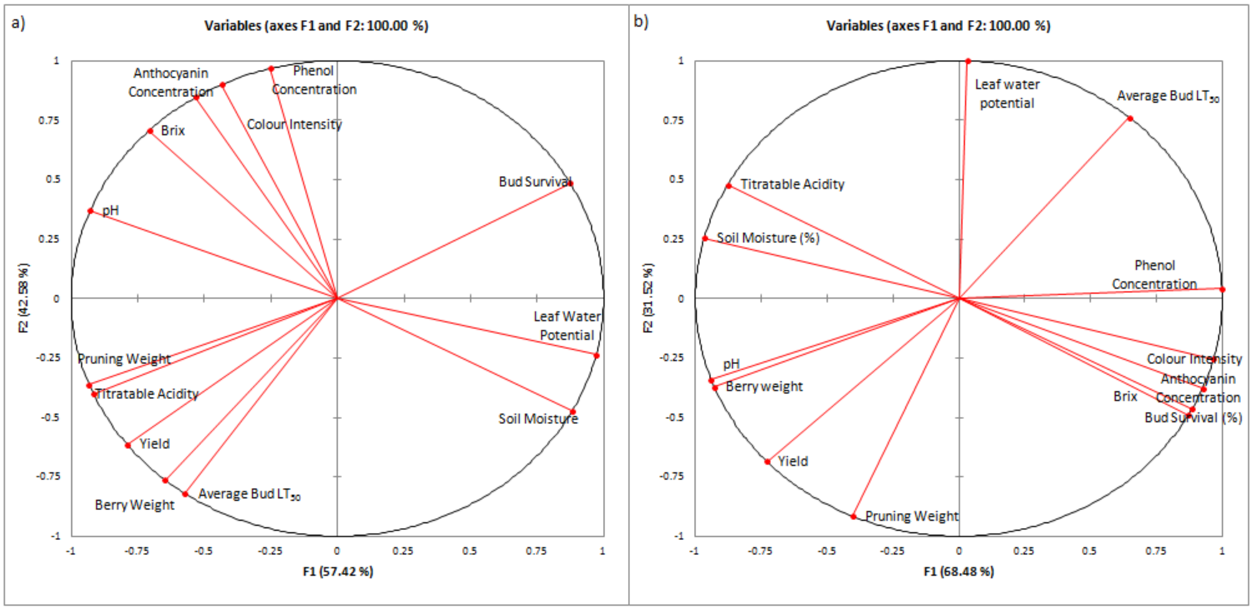


Figure 4.1 Principal component analysis diagrams of the Buis Cabernet franc vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

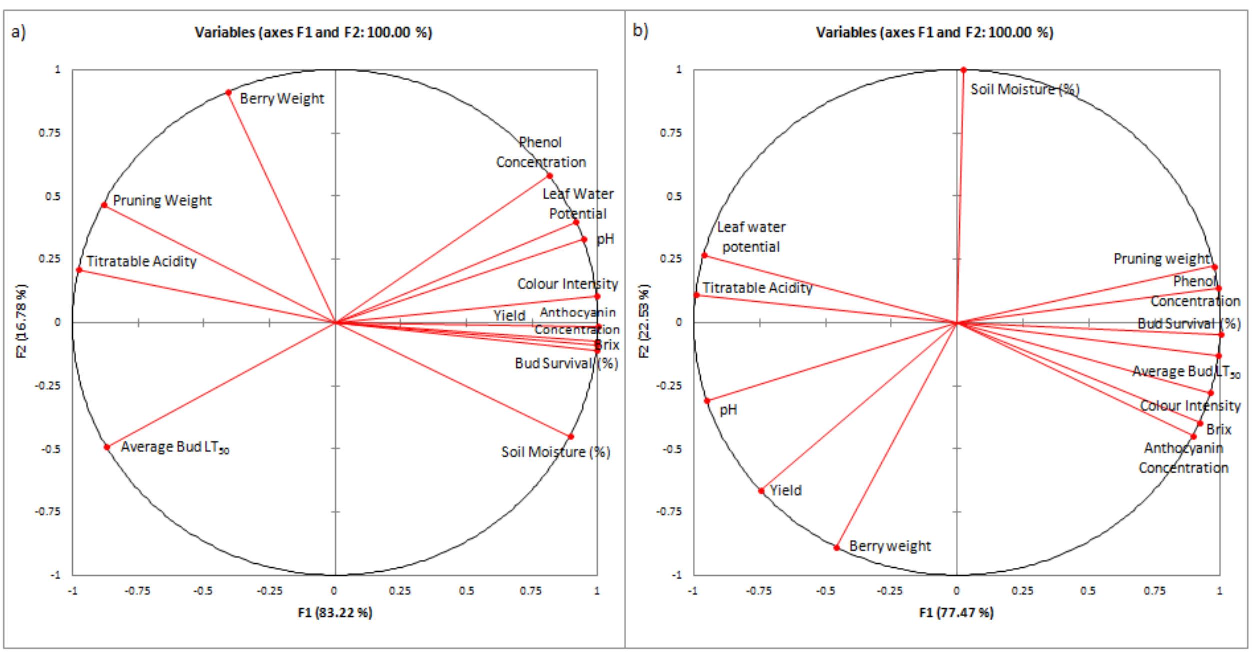


Figure 4.2 Principal component analysis diagrams of the George Cabernet franc vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

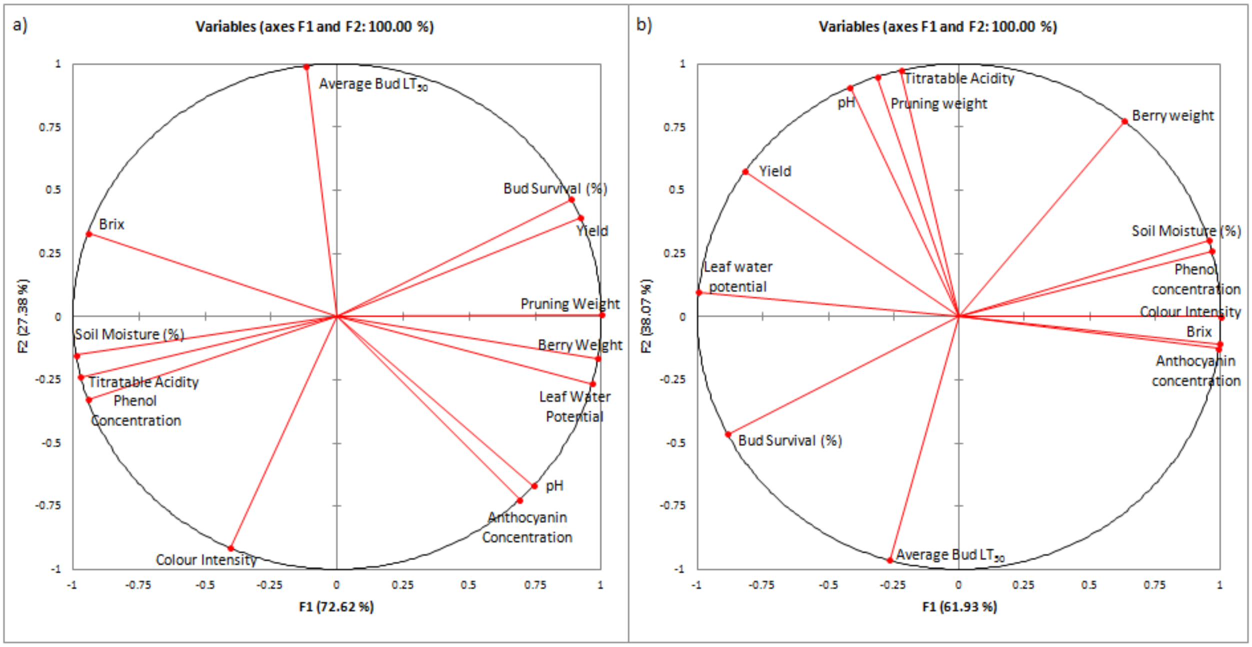


Figure 4.3 Principal component analysis diagrams of the Kocsis Cabernet franc vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

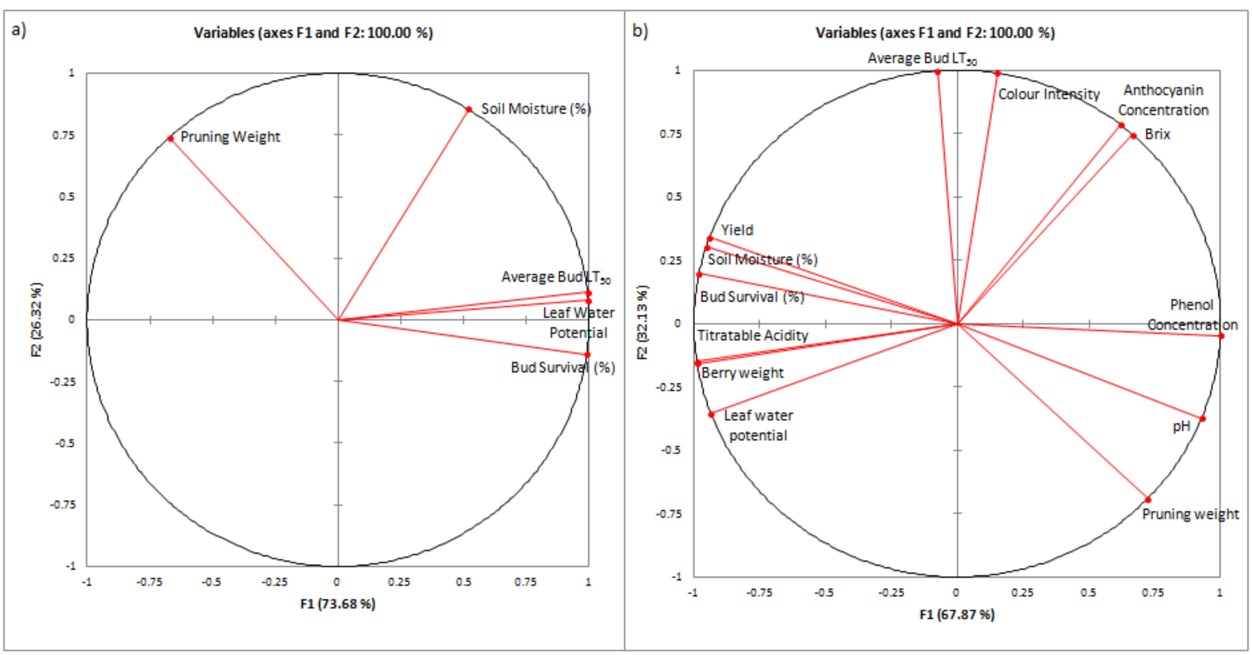


Figure 4.4 Principal component analysis diagrams of the Lambert Cabernet franc vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

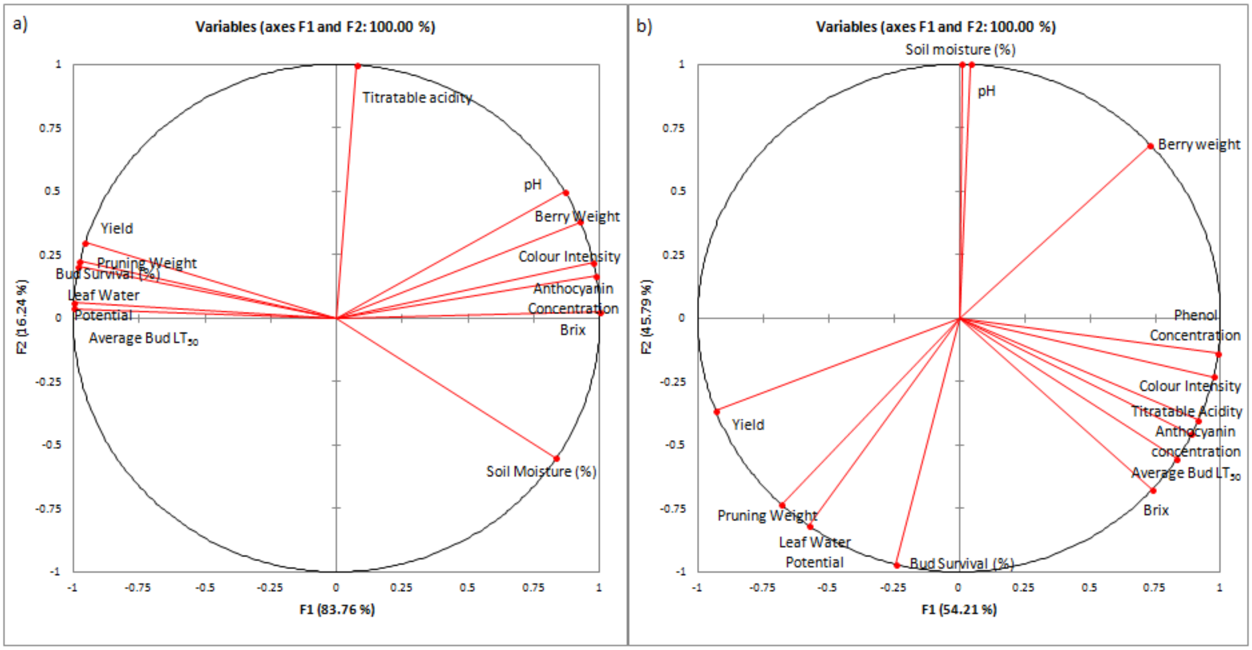


Figure 4.5 Principal component analysis diagrams of the Cave Spring Cabernet franc vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors. Phenol concentration relationships are not shown in a) since this variable was not analysed due to strong collinearity trends.

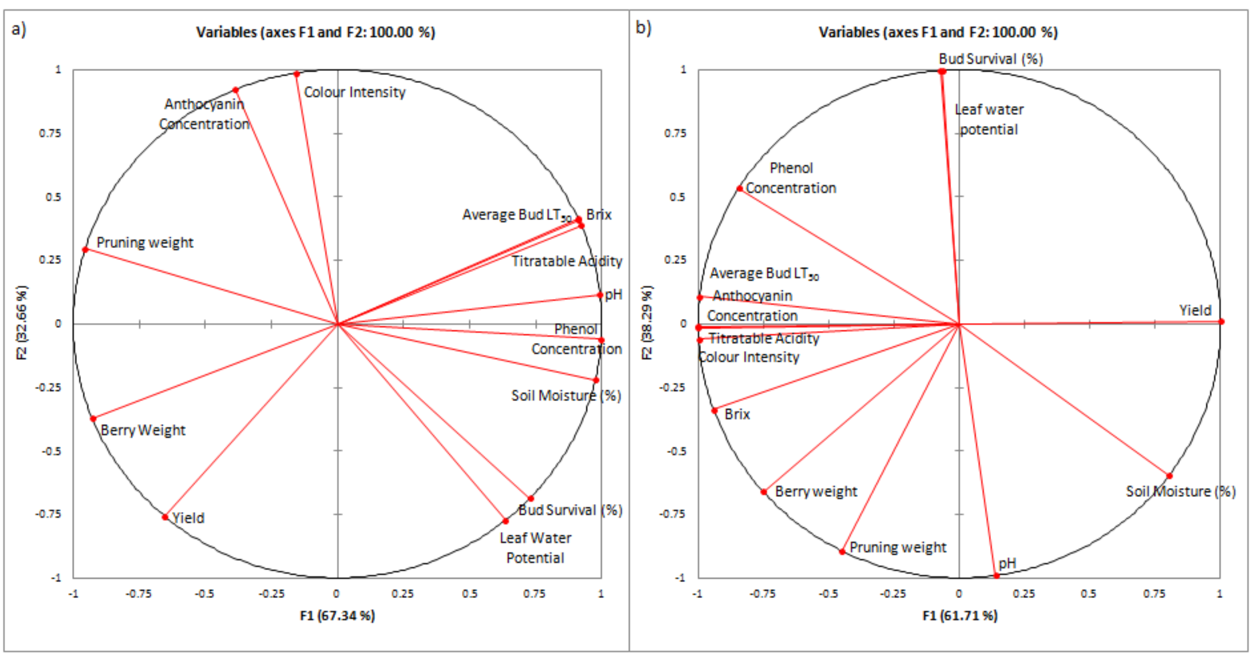


Figure 4.6 Principal component analysis diagrams of the Lowrey Cabernet franc vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

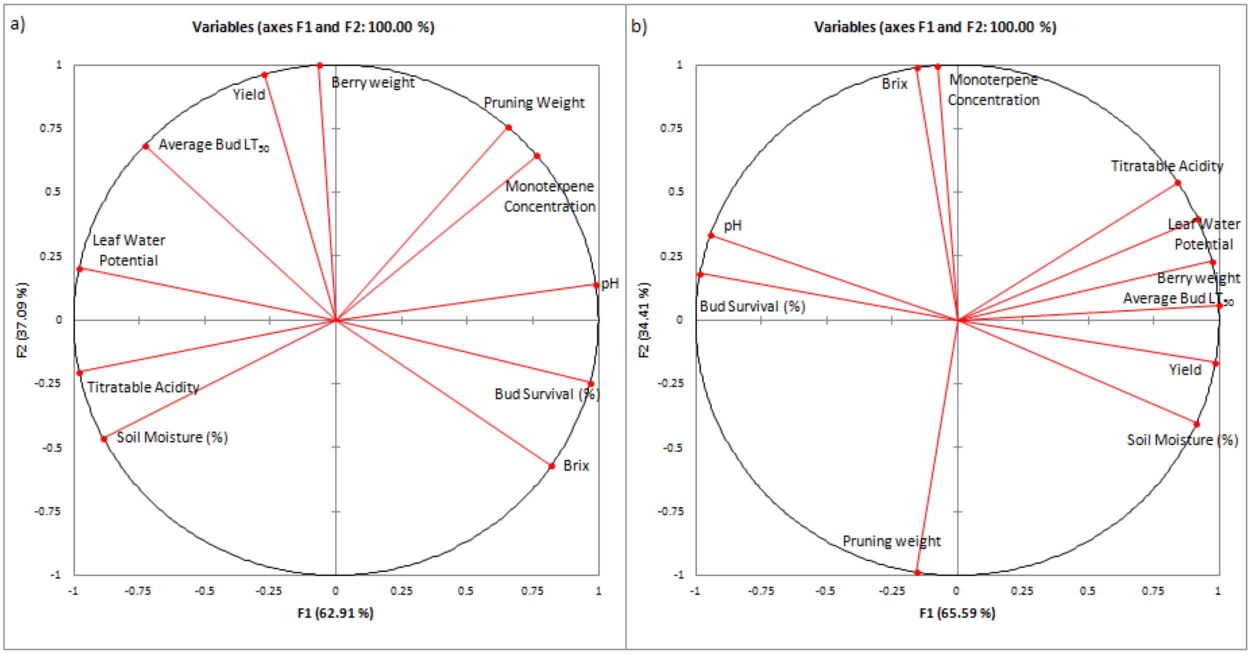


Figure 4.7 Principal component analysis diagrams of the Buis Riesling vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

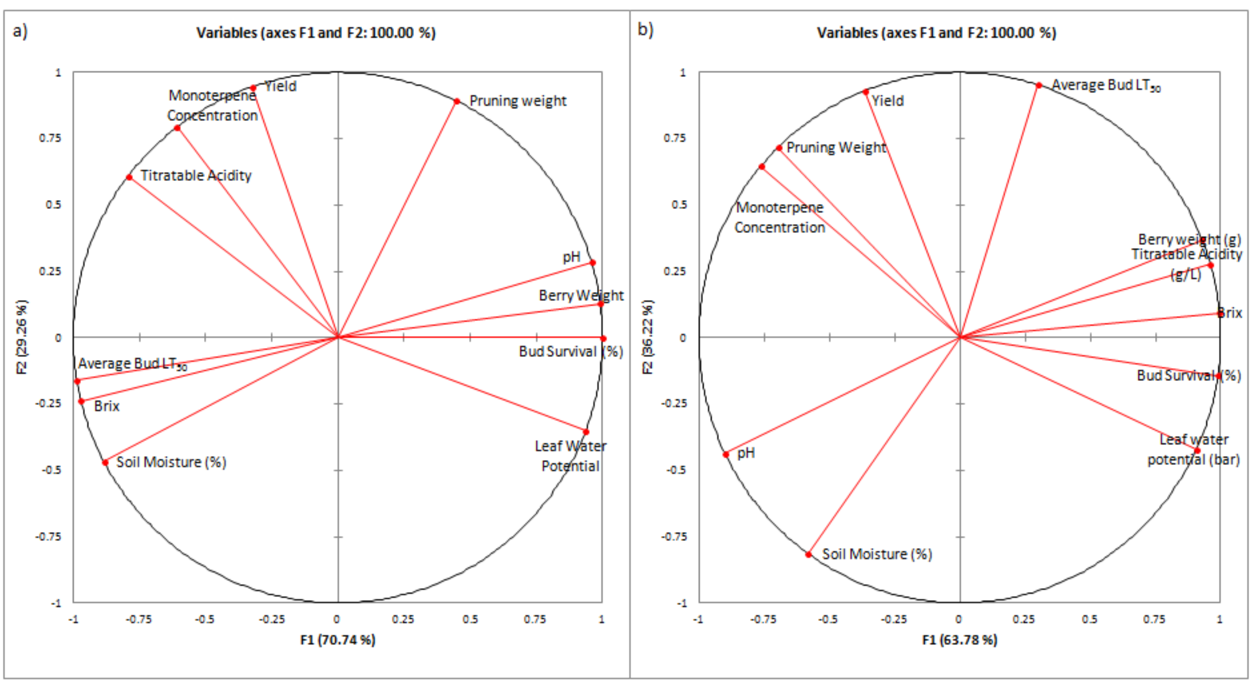


Figure 4.8 Principal component analysis diagrams of the George Riesling vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

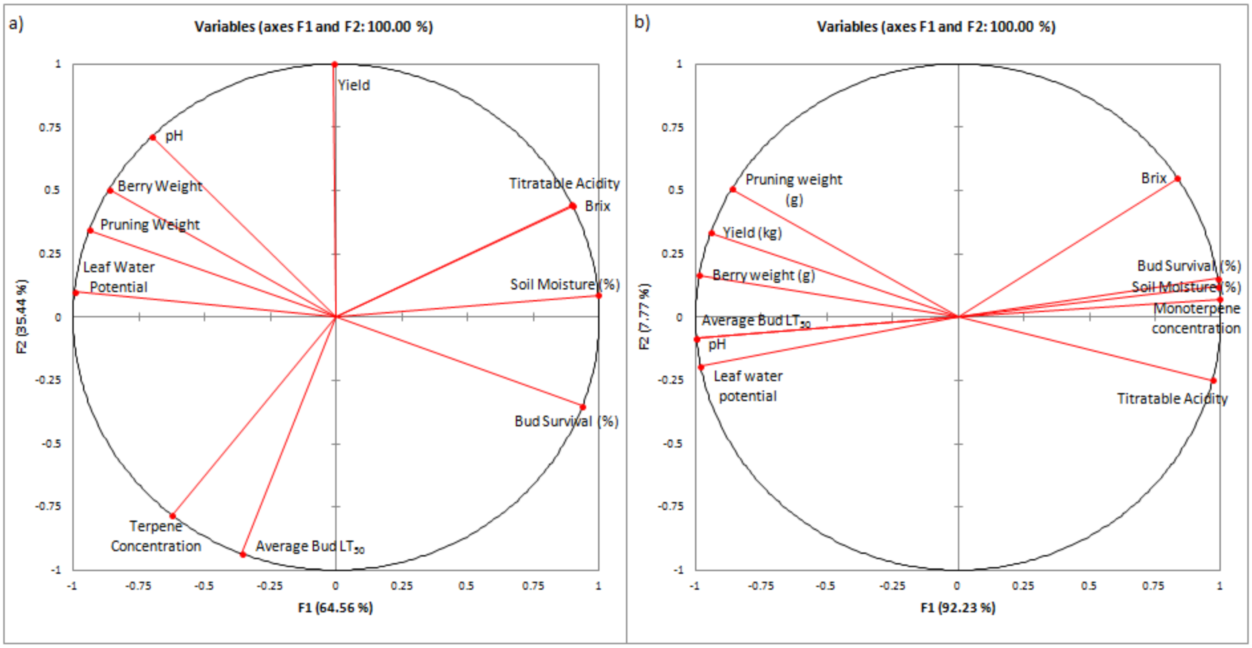


Figure 4.9 Principal component analysis diagrams of the Hughes Riesling vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

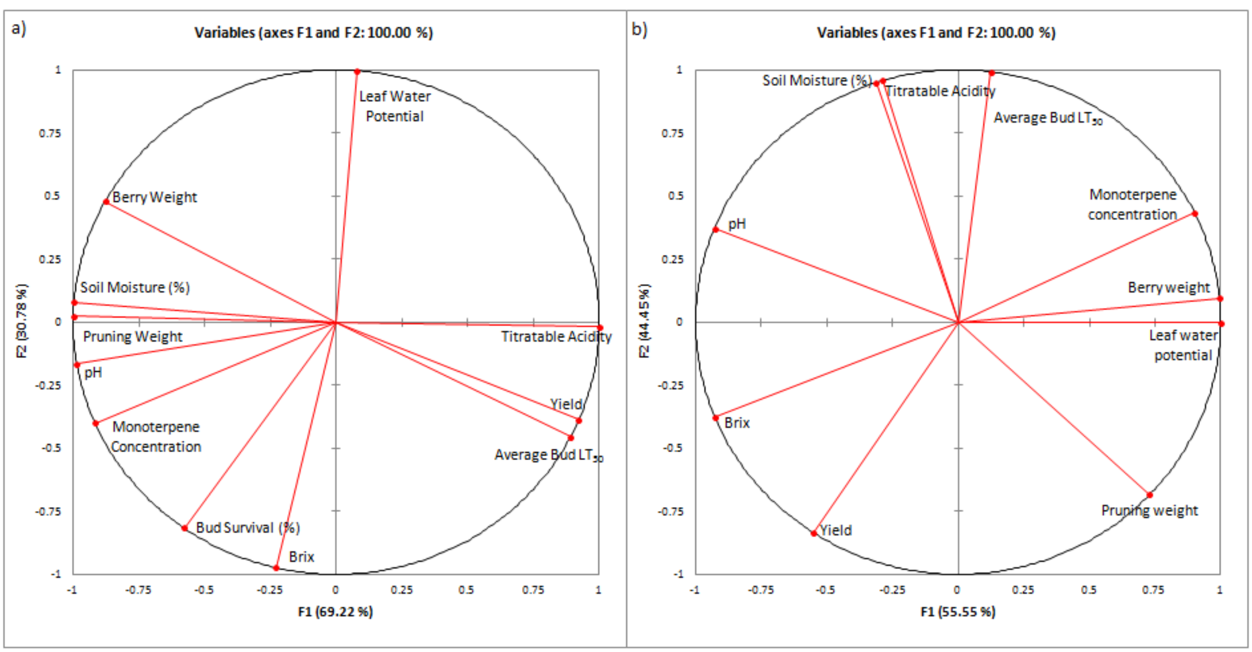


Figure 4.10 Principal component analysis diagrams of the Lambert Riesling vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

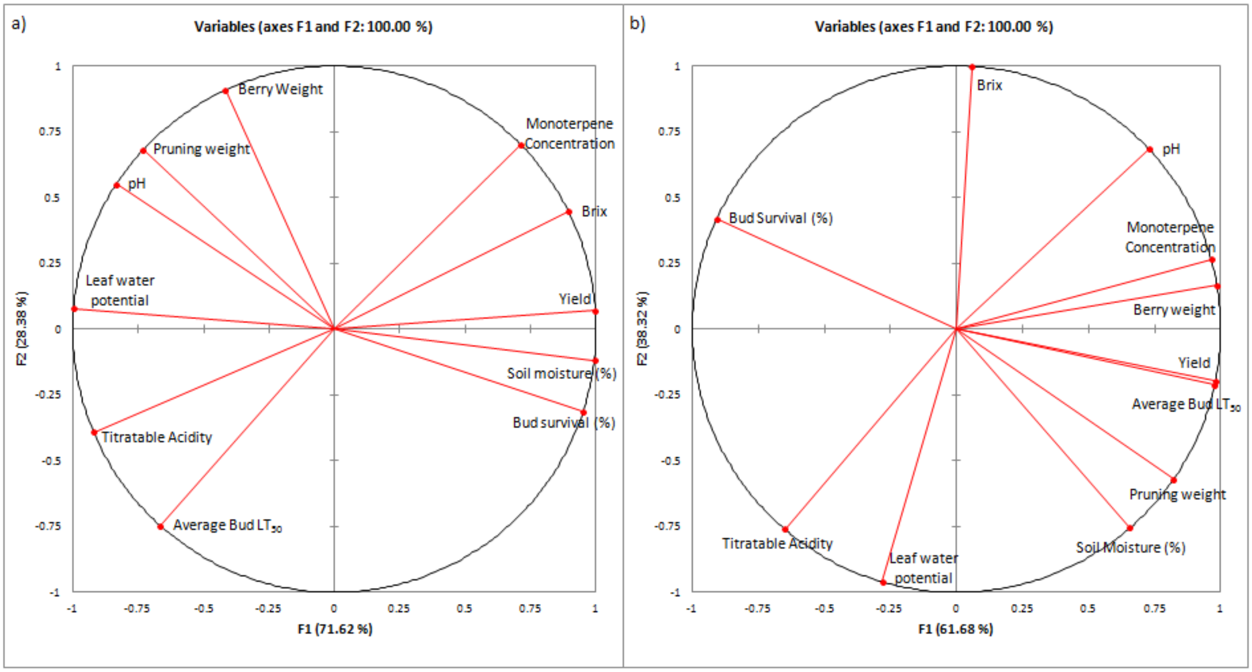


Figure 4.11 Principal component analysis diagrams of the Cave Spring Riesling vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

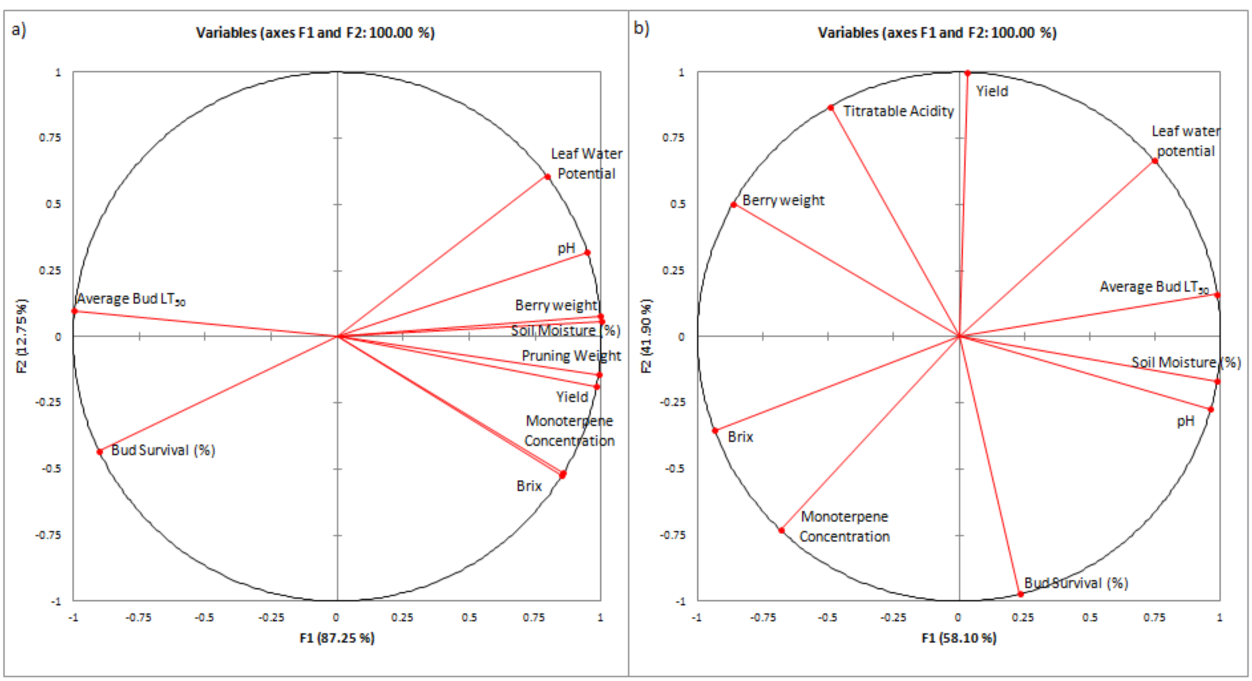


Figure 4.12 Principal component analysis diagrams of the Lowrey Riesling vineyard block for a) 2010 and b) 2011. Variables include winter hardiness, vine, and berry composition characteristics. PCA was run with three clusters and two factors.

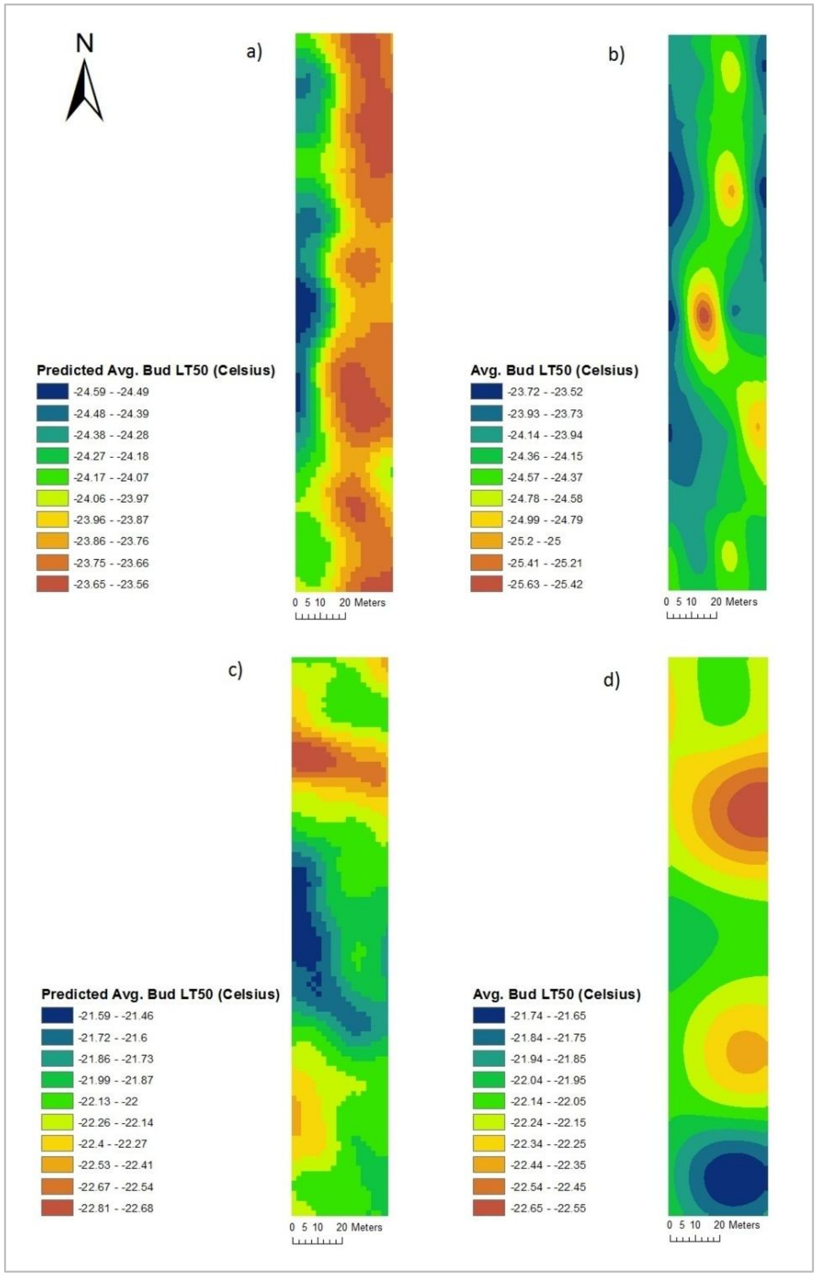


Figure 4.13 Maps of mean bud LT50 predictions vs. measured values for the Buis Cabernet franc block in 2010 and 2011. a) 2010 bud LT_{50} prediction; b) 2010 mean bud LT50; c) 2011 bud LT_{50} prediction; d) 2011 mean bud LT50.

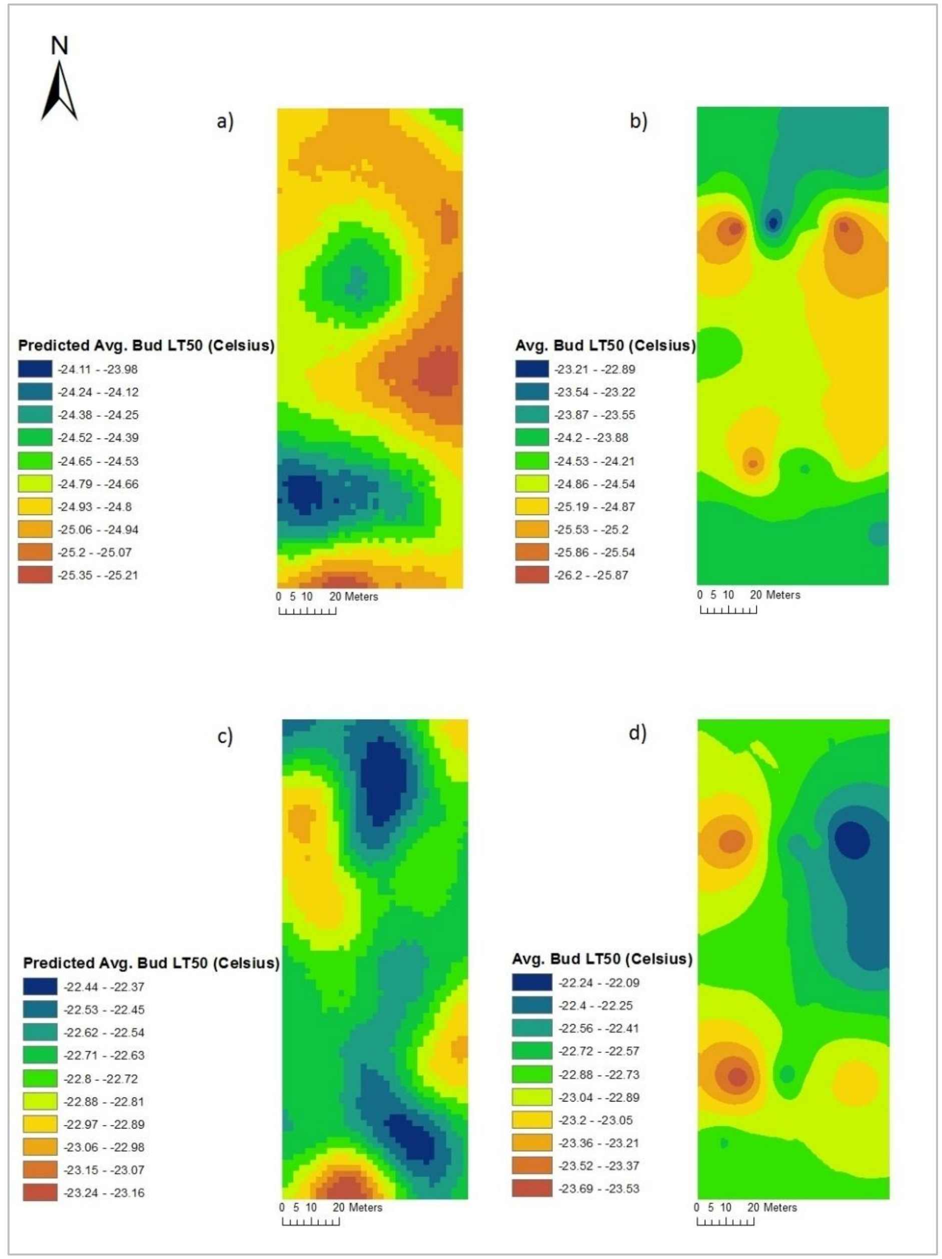


Figure 4.14 Maps of mean bud LT50 predictions vs. measured values for the George Cabernet franc block in 2010 and 2011. a) 2010 bud LT_{50} prediction; b) 2010 mean bud LT50; c) 2011 bud LT_{50} prediction; d) 2011 mean bud LT50.

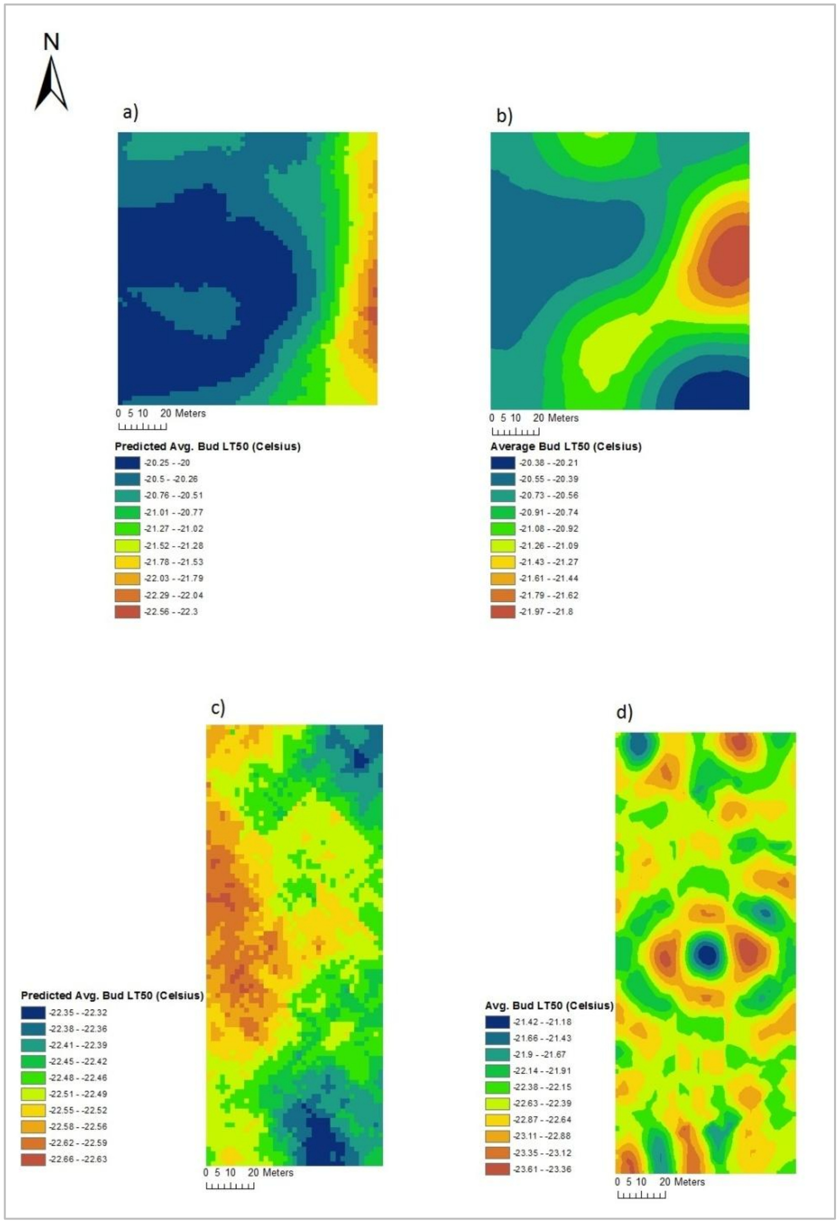


Figure 4.15 Maps of mean bud LT50 predictions vs. measured values for the Kocsis Cabernet franc block in 2011 and the Lambert Cabernet franc block in 2011. a) Kocsis 2011 bud LT_{50} prediction; b) Kocsis 2011 mean bud LT50; c) Lambert 2011 bud LT_{50} prediction; d) Lambert 2011 mean bud LT50.

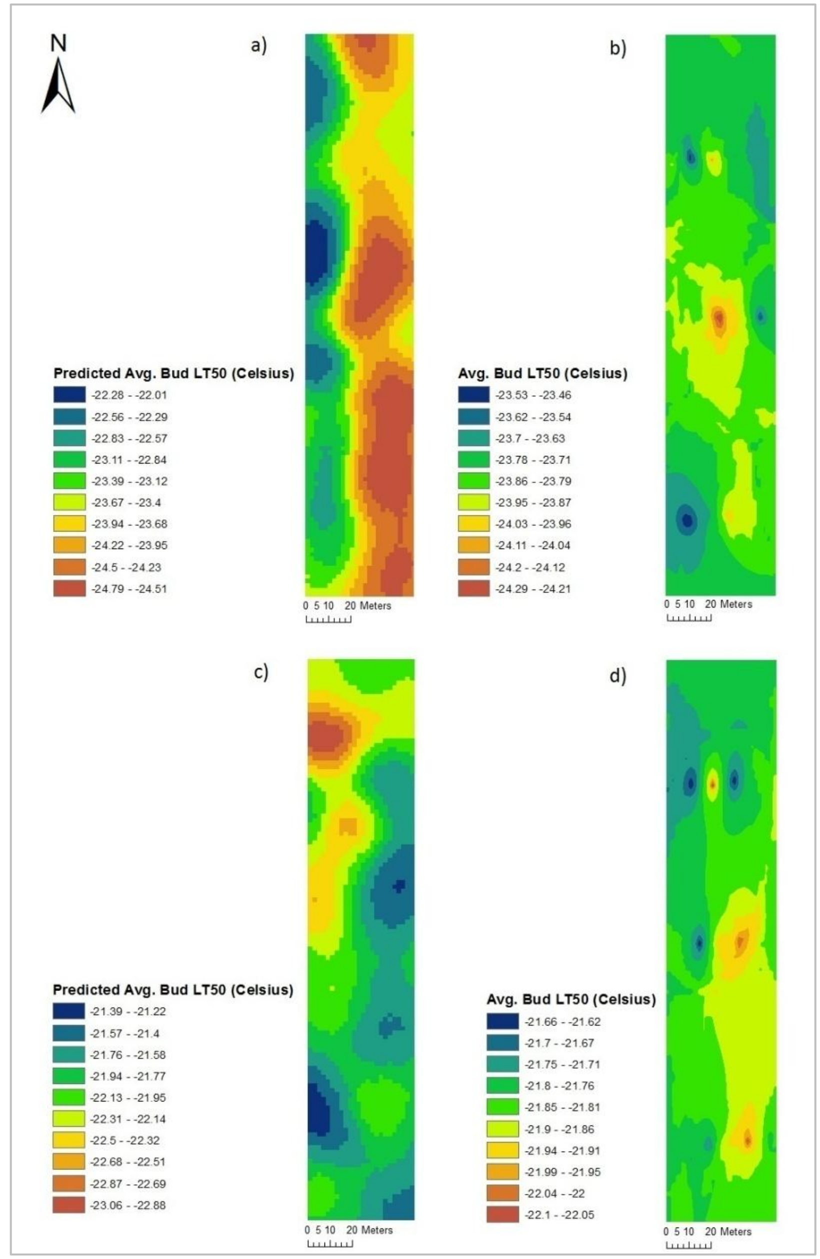


Figure 4.16 Maps of mean bud LT50 predictions vs. measured values for the Cave Spring Cabernet franc block in 2010 and 2011. a) 2010 bud LT_{50} prediction; b) 2010 mean bud LT50; c) 2011 bud LT_{50} prediction; d) 2011 mean bud LT50.

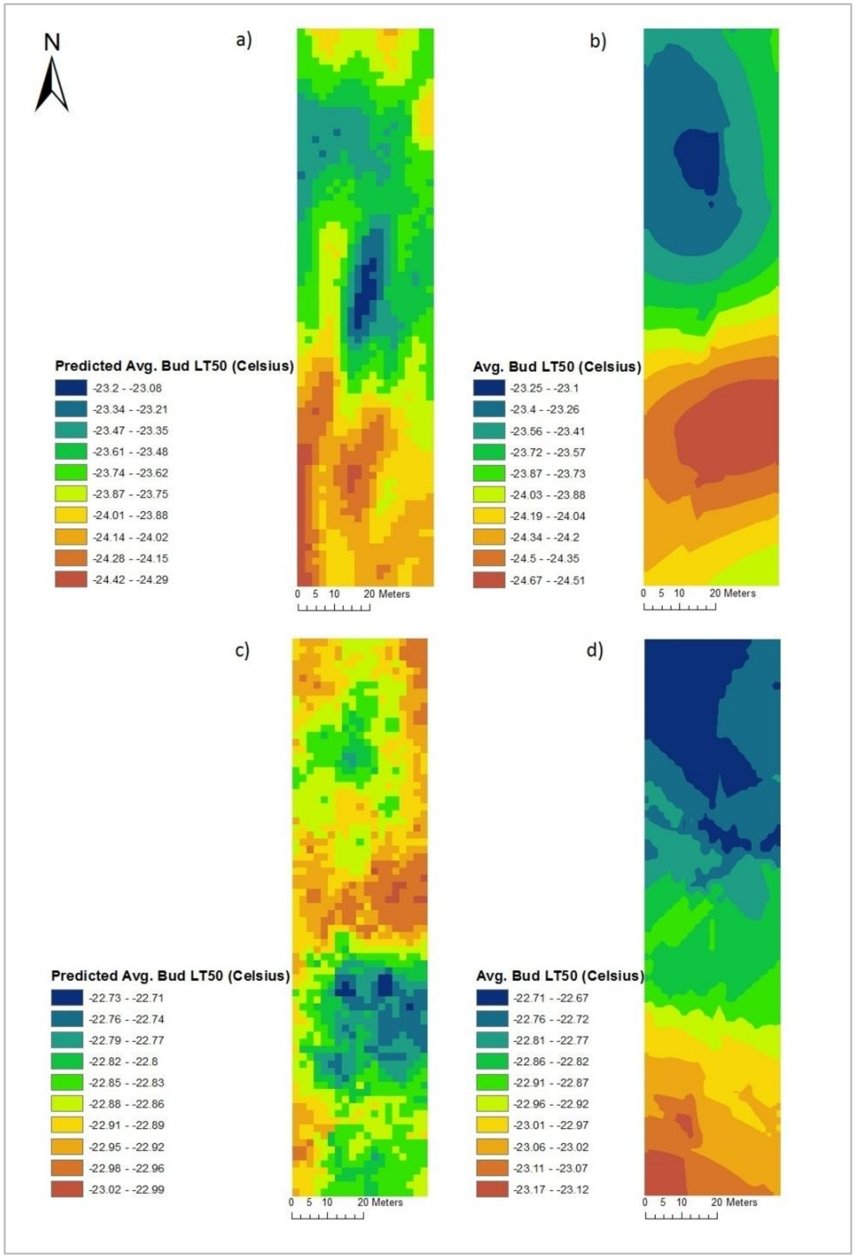


Figure 4.17 Maps of mean bud LT_{50} predictions vs. measured values for the Lowrey Cabernet franc block in 2010 and 2011. a) 2010 bud LT_{50} prediction; b) 2010 mean bud LT_{50}; c) 2011 bud LT_{50} prediction; d) 2011 mean bud LT50.

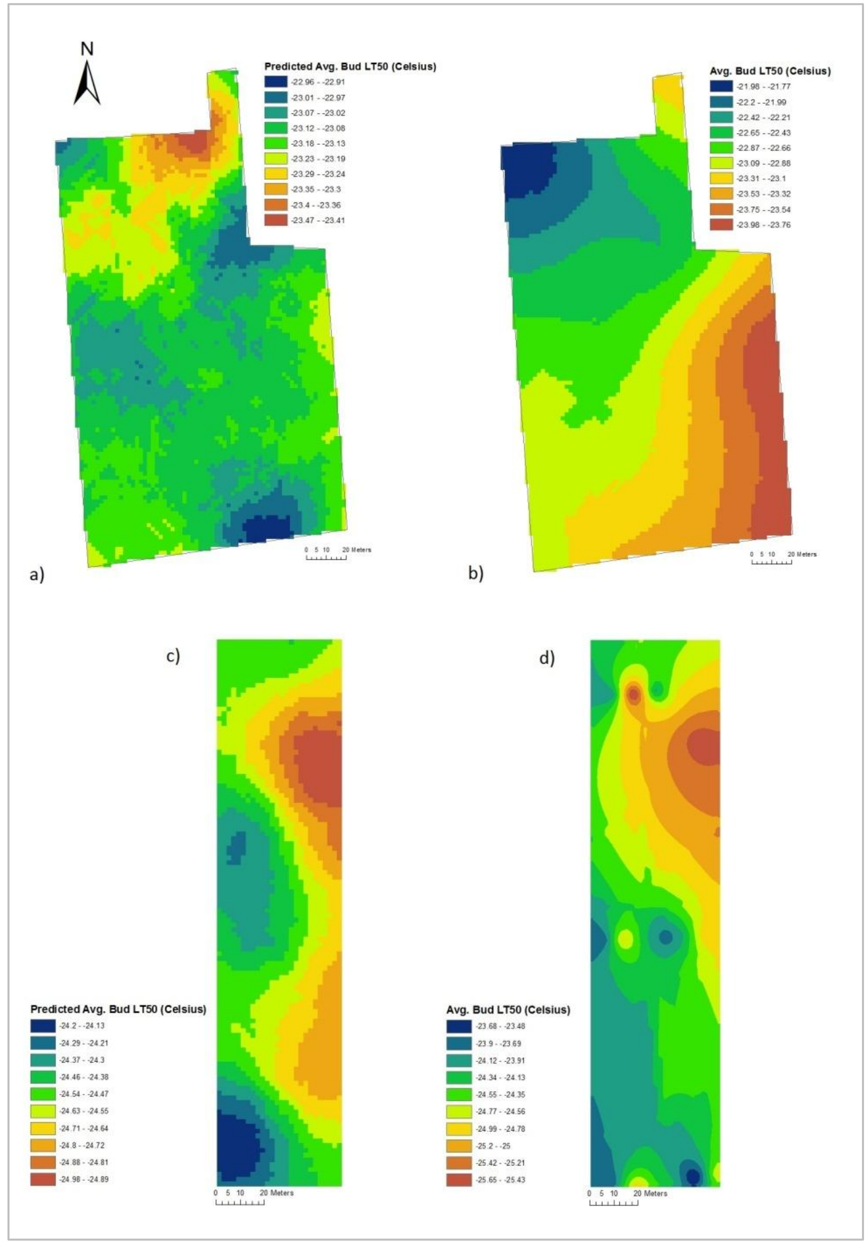


Figure 4.18 Maps of mean bud LT_{50} predictions vs. measured values for the Buis Riesling block in 2011 and the Hughes Riesling block in 2010. a) Buis 2011 bud LT_{50} prediction; b) Buis 2011 mean bud LT_{50}; c) Hughes 2010 bud LT_{50} prediction; d) Hughes 2010 mean bud LT_{50}.

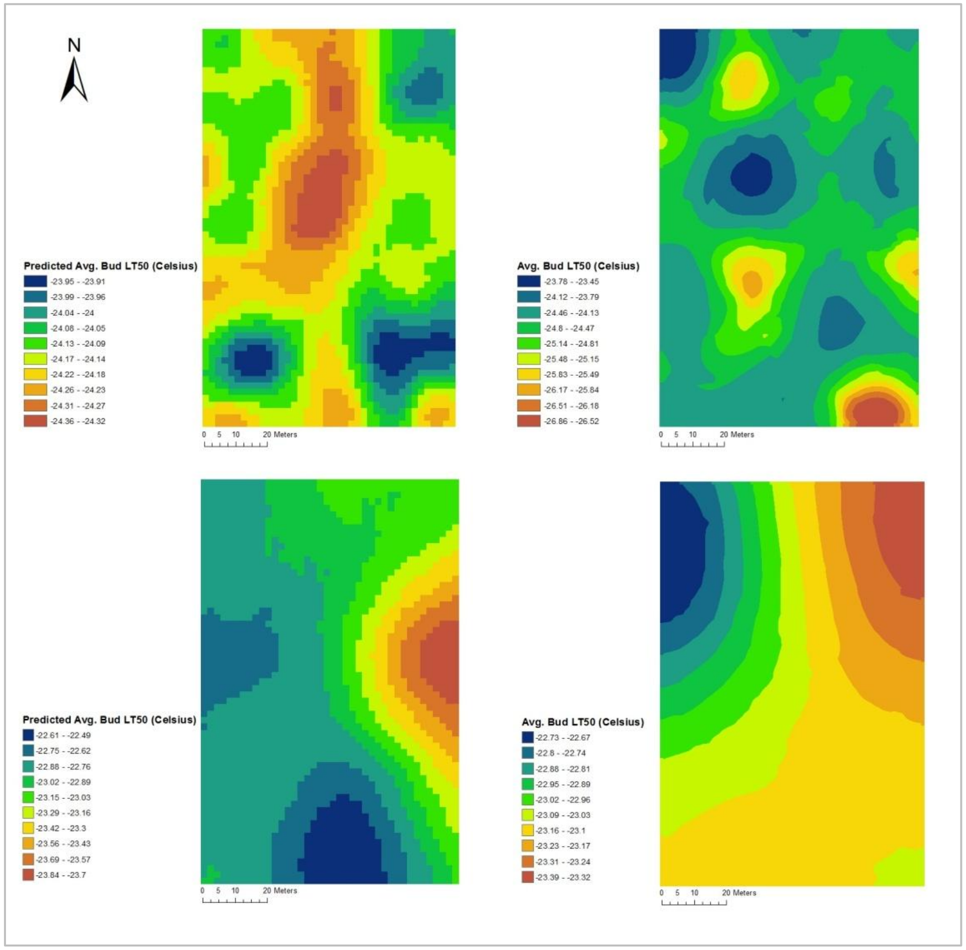


Figure 4.19 Maps of mean bud LT50 predictions vs. measured values for the George Riesling block in 2010 and 2011. a) 2010 bud LT_{50} prediction; b) 2010 mean bud LT50; c) 2011 bud LT_{50} prediction; d) 2011 mean bud LT50.

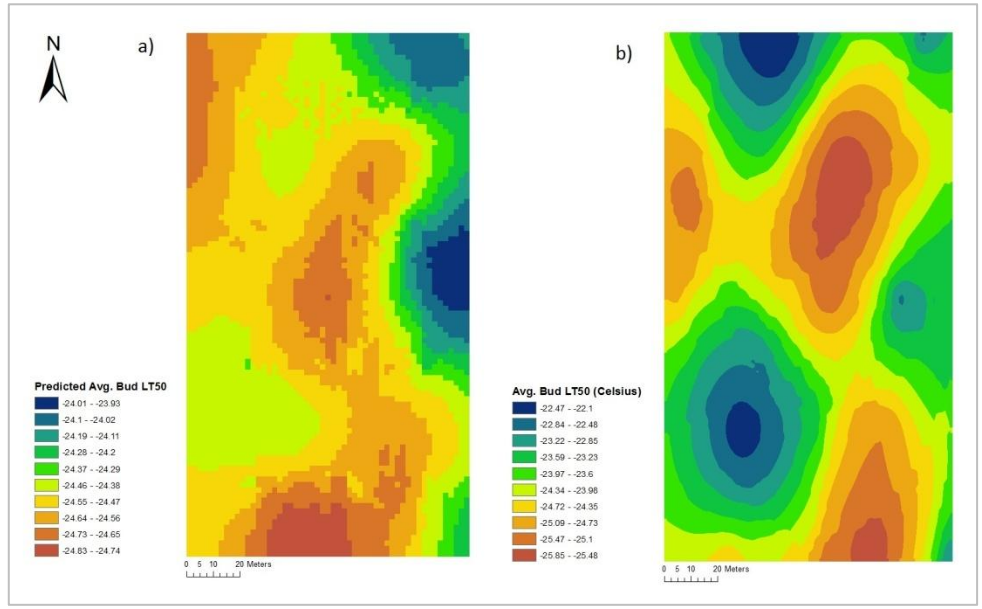


Figure 4.20 Map of mean bud LT50 predictions vs. measured values for the Cave Spring Riesling block in 2010. a) 2010 bud LT_{50} prediction; b) 2010 mean bud LT50.

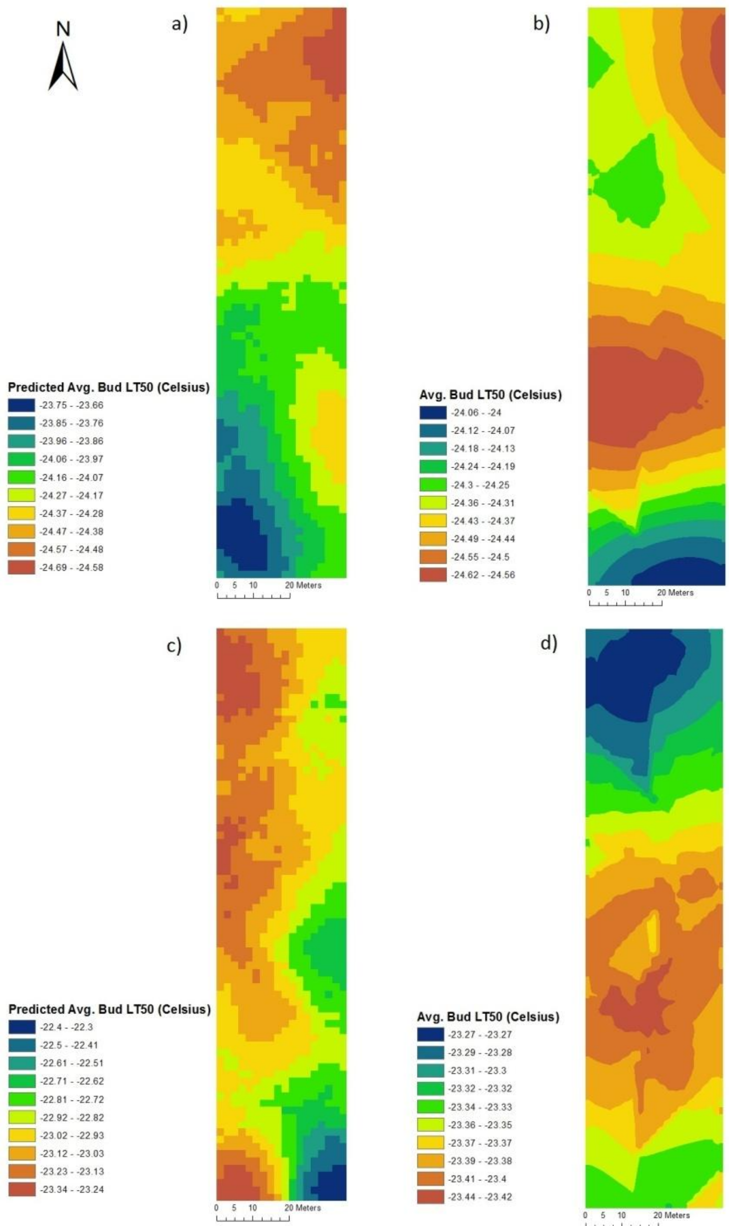


Figure 4.21 Maps of mean bud LT50 predictions vs. measured values for the Lowrey Riesling block in 2010 and 2011. a) 2010 bud LT_{50} prediction; b) 2010 mean bud LT50; c) 2011 bud LT_{50} prediction; d) 2011 mean bud LT50.

General Discussion and Conclusions

The objective of this thesis was to investigate the spatial relationships of winter hardiness and its relationships with other important *terroir* factors such as soil moisture, water status, yield, and fruit composition. With the application of DTA, GIS, and various statistical procedures, it was possible to assess the spatial (and statistical) relationships among these variables. It was hypothesized that soil moisture, leaf ψ, and yield would be spatially correlated to bud LT_{50} values, and that further relationships between LT_{50} values and fruit composition and vine size would be uncovered. To support this hypothesis, it was expected that water metrics, yield, and hardiness measurements would be temporally stable over the two year study period to further develop the *terroir* of the Niagara wine region. Additionally, it was also expected that water metrics and yield measurements would be related to fruit composition.

In the first part of this study, it was hypothesized that soil moisture, leaf ψ, and yield would be associated with one another and that they would be related to berry composition variables. The results supported the acceptance of these hypotheses. Leaf ψ and yield were often directly related to one another, and were related to measurements of berry composition variables. Thus, areas of low leaf ψ and yield led to the production of smaller berries with greater concentrations of sugar and phenolic analytes for Cabernet franc blocks, and smaller berries with lower TA, higher pH, and higher Brix for Riesling blocks. Soil moisture and vine size both showed inconsistent relationships with variables studied, possibly due to the method of soil moisture measurements, vineyard variability, and vine management practices.

It was further hypothesized in this study that spatial patterns of soil moisture, leaf ψ, yield, mean bud LT_{50}, and bud survival would be temporally stable over the study period. It was also expected that monthly bud LT_{50} patterns would show temporal trends as well. With the exception of bud survival, this hypothesis was supported. Temporally stable patterns existed for soil moisture, leaf ψ, yield, and mean bud LT_{50} values. Cultivar differences appeared when reviewing leaf ψ, mean bud LT_{50} patterns, and bud survival. Although bud survival did not show strong temporal trends, it suggested that Cabernet franc blocks became more winter hardy more quickly and had better rates of survival than

Riesling. Discoveries in this study therefore suggest that temporal patterns existed within the vineyard blocks studied.

Lastly, it was hypothesized that relationships between mean bud LT_{50}, water metrics (soil moisture, leaf ψ), and yield would be found for both Cabernet franc and Riesling cultivars within the Niagara region. Using correlation tests, PCA, multilinear regression, and GIS procedures this hypothesis was successfully supported. For Cabernet franc blocks, bud hardiness was promoted by high soil moisture, low leaf ψ, and high yield. These patterns changed between blocks. For Riesling, bud hardiness relationships were constant from block to block, with low mean bud LT_{50} values being indicated by low soil moisture, leaf ψ, and yield.

The findings of the three chapters described above help to support the main hypothesis – that soil moisture, leaf ψ, and yield would be spatially correlated to bud LT_{50} values, and that further relationships between LT_{50} values and fruit composition and vine size would be found. Spatial patterns of soil moisture, water status, and yield were temporally stable over the study period and were related to berry composition variables. With the additional temporal stability of bud LT_{50} values and their relationships with the variables previously described, it can be stated that bud hardiness characteristics are an important factor in the *terroir* of the Niagara Peninsula - a wine region which supports the existence of many cold hardy *Vitis vinifera* cultivars. In the future, further work should be done to explore the relationship between bud hardiness measurements in the lab and field measurements. Additionally, GIS methods should be further explored and improved in order to make these spatial studies more robust.

Appendices

I) Tables

Table A1 General features of Niagara Peninsula Cabernet franc and Riesling vineyards used within the study during the 2010-2011 and 2011-2012 sampling years.

Variable	**Cabernet franc sites**					
	Buis	**George Vineyard**	**Kocsis Vineyard**	**Lambert**	**Cave Spring**	**Lowrey**
VQA sub-appellation	Four Mile Creek	Lincoln Lakeshore (north)	Lincoln Lakeshore (south)	Niagara Lakeshore	Beamsville Bench	St. Davids Bench
Area of vineyard block (ha)	0.78	0.94	1.15	1.19	0.92	0.43
Number of sentinel vines	76	72	81	77	75	84
Soil series (Kingston and Presant 1989)	Jeddo 8 B>B	Chinguacousy 24 (Washed Phase; CGU.W)	Trafalgar 7: c>B	Chinguacousy 19: B=B	Chinguacousy 14 (Loamy Phase; CGU.L)	Brantford 12
Parent materials	Mainly reddish hued clay loam till	Washed clay loam till, modified by lacustrine processes	15-40 cm loamy textures over reddish-hued silty clay loam > 1 m thick over Queenston shale bedrock	Mainly reddish-hued clay loam till	15-40 cm loamy textures over clay loam till	Lacustrine silty clay
Soil drainage	Poor	Imperfect-poor	Imperfect	Imperfect to poor	Imperfect	Moderately well
Rootstock	SO4 + 3309	SO4		SO4	101-14	3309
Vine age at initiation of trial (year planted)	1987	1995		2000	1999	2007
Vine spacing (m; row X vine)	2.9 X 1.3	2.7m X 1.4	2.75 X 1.72	2.7 X 1.2	2.7 X 1.44	2.8 X 1.25
Number of rows; vines per row	56 rows , 8300 vines	24 rows	77	15 rows; 2400 vines	23 rows	14
	118 vines/ row	137 vines/ row	96 vines/row	160 vines/row	233 vines/row	137 vines/ row
Training system	Guyot	Guyot	Guyot	Guyot	Guyot	Guyot
Floor management	Clean	sod	Clean	Alternate sod	Alternate sod	Alternate sod

Table A1 **(**Continued)

Variable	**Riesling sites**					
	Buis	**George Vineyard**	**Hughes Vineyard**	**Lambert**	**Cave Spring**	**Lowrey**
VQA sub-appellation	Niagara Lakeshore	Lincoln Lakeshore (north)	Lincoln Lakeshore (south)	Four Mile Creek	Beamsville Bench	St. David's Bench
Area of vineyard block (ha)	2.55	0.89	0.97	0.54	1.89	0.43
Number of sentinel vines	74	70	72	75	75	84
Soil series (Kingston and Presant 1989)	Tavistock 15; c >B	Chinguacousy 24 (Washed Phase; CGU.W)	Jeddo 1 (1/3) North, Chinguacousy (2/3) South	Chinguacousy 19; B=B	Chinguacousy 14; c>B	Brantford 12
Parent materials	40-100 cm reddish-hued loamy textures over clay loam till	Washed clay loam till, modified by lacustrine processes	Mainly clay loam till	Mainly reddish-hued clay loam till	15-40 cm loamy textures over clay loam	Lacustrine silty clay
Soil drainage	Imperfect	Imperfect to-poor	Poor	Imperfect to poor	Imperfect to poor	Moderately well
Rootstock	SO4	SO4	3309	SO4	SO4	3309
Vine age at initiation of trial (year planted)	1996	1995	2006	2000	1978	2007
Vine spacing (m; row X vine)	2.5 X 1.5	2.7 X 1.4	2.8 X 1.25	2.7 X 1.2	2.5 X 1.5	2.2 X 0.9
Number of rows; vines per row	58 rows; 10,940 vines 42 @ 198v/r, 16 @ 164v/r	29 rows 137 vines/ row	58 rows 137 vines/ row	15 rows; 2400 vines 160 vines/row	45 rows; 6120 136 vines/row	14 376 vines/ row
Training system	Scott Henry	Guyot	Guyot	Scott Henry	Pendelbogen	Guyot
Floor management	Clean cultivation	Sod	Alternate sod	Alternate sod	Alternate sod	Clean

Table A2 Pearson's correlation results for soil moisture and leaf water potential for six Ontario Cabernet franc blocks in 2010 and 2011. Berry composition variables are listed first, followed by vine characteristics. The correlation values and significance level are stated. * = p<0.05, ** = p<0.01, *** = p<0.001 Abbreviations: TA (titratable acidity); LWP (leaf water potential). Phenol concentrations and soil moisture showed no relationships with leaf water potential and are therefore not included.

Soil moisture											
Vineyard block	**Year**	**Yield**	**Berry weight**	**pH**	**Brix**	**TA**	**Anthocyanins**	**Colour**	**Phenols**	**LWP**	**Vine size**
Buis	2010					-0.291*		-0.244*			
Buis	2011			0.268*						0.236*	
George	2010										
George	2011			-0.418***	-0.358**	0.233*		-0.238*			
Kocsis	2010	-0.530***	-0.433***		0.346**		0.224*	0.338**	0.535***		-0.378***
Kocsis	2011				-0.327**						-0.232*
Lambert	2010										
Lambert	2011										
Cave Spring	2010	-0.327**	0.378***								
Cave Spring	2011		0.396***				-0.301**	-0.338**	-0.328**		
Lowrey	2010				0.250*				0.437***		
Lowrey	2011										

Leaf water potential									
Vineyard block	**Year**	**Yield**	**Berry weight**	**pH**	**Brix**	**TA**	**Anthocyanins**	**Colour**	**Vine size**
Buis	2010								
Buis	2011	-0.459*							
George	2010		0.498*				-0.626**	-0.641**	
George	2011				-0.559*	0.814***	-0.560*		
Kocsis	2010	0.514*	0.587**			0.570*			0.506*
Kocsis	2011	0.595*							0.485**
Lambert	2010								
Lambert	2011		0.487*						
Cave Spring	2010								0.649**
Cave Spring	2011								
Lowrey	2010	-0.459*		0.470*					0.741***
Lowrey	2011					0.489*			0.421*

Table A3 Pearson's correlation results for yield for six Ontario Cabernet franc blocks in 2010 and 2011. Berry composition variables are listed first, followed by vine characteristics. The correlation values and significance level is stated. * = $p<0.05$, ** = $p<0.01$, *** = $p<0.001$ Abbreviations: TA (titratable acidity), LWP (leaf water potential).

		Variable									
Vineyard block	**Year**	**Berry weight**	**pH**	**Brix**	**TA**	**Anthocyanins**	**Colour**	**Phenols**	**Soil moisture**	**LWP**	**Vine size**
Buis	2010		-0.228*	-0.579***		-0.366**	-0.415***				0.421***
Buis	2011	0.386***		-0.385***		-0.414***	-0.383***	-0.380***		-0.459*	0.577***
George	2010	0.467***		-0.247*		-0.326**	-0.295*				
George	2011	0.504***		-0.501***	0.243*		-0.428***	-0.555***			
Kocsis	2010	0.718***						-0.506***	-0.530***	0.514*	0.670***
Kocsis	2011									0.595*	0.673***
Lambert	2010										
Lambert	2011			-0.245*				-0.241*			
Cave Spring	2010	-0.417***				-0.392***	-0.438***	-0.237*	-0.327**		
Cave Spring	2011	-0.302**		-0.322**	-0.291*						0.257*
Lowrey	2010	0.382***	-0.366***	-0.476***	-0.229*	-0.252*	-0.272*	-0.311**		-0.459*	
Lowrey	2011	0.434***		-0.582***		-0.459***	-0.577***	-0.365***			0.336**

Table A4 Pearson's correlation results for soil moisture and leaf water potential for six Ontario Riesling blocks in 2010 and 2011. The correlation values and significance level is stated. * = p<0.05, ** = p<0.01, *** = p<0.001 Abbreviations: TA (titratable acidity) and LWP (leaf water potential). Monoterpene concentrations and vine size were not significantly correlated for any blocks for soil moisture while pH was nonsignificant for all blocks vs. leaf water potential. There were no significant correlations for the Lowrey Vineyard.

		Soil moisture							
Vineyard block	**Year**	**Yield (kg)**	**Berry weight (g)**	**pH**	**Brix**	**TA (g/L)**	**Monoterpenes**	**LWP**	**Vine size**
Buis	2010								
Buis	2011			0.370***					
George	2010			-0.306*		0.267*		0.445*	
George	2011	-0.296*			0.291*	-0.283*			
Hughes	2010								
Hughes	2011							-0.727***	
Lambert	2010								
Lambert	2011								
Cave Spring	2010			-0.234*					
Cave Spring	2011		-0.234*	-0.289*		-0.236*			
		Leaf water potential							
Vineyard block	**Year**	**Yield**	**Berry weight**	**pH**	**Brix**	**TA**	**Monoterpenes**	**Soil moisture (%)**	**Vine size**
Buis	2010								
Buis	2011								
George	2010				0.575**	-0.471*	0.445*		
George	2011		-0.552*		0.530*	-0.570*			
Hughes	2010		0.667**					0.651**	
Hughes	2011		0.787***			-0.560*	-0.727***		
Lambert	2010		0.694***						
Lambert	2011			-0.517*	0.551*				
Cave Spring	2010	-0.527*							
Cave Spring	2011		0.541*						

Table A5 Pearson's correlation results for yield for six Ontario Riesling blocks in 2010 and 2011. Berry composition variables are listed first, followed by vine characteristics. The correlation values and significance level is stated. * = p<0.05, ** = p<0.01, *** = p<0.001 Abbreviations: TA (titratable acidity), and LWP (leaf water potential). Monoterpene concentrations were not significantly correlated for any blocks.

		Variable						
Vineyard block	**Year**	**Berry weight**	**pH**	**Brix**	**TA**	**Soil moisture**	**LWP**	**Vine size**
Buis	2010	0.254*		-0.449***	0.309**			
Buis	2011			-0.332**				
George	2010			-0.287*				0.570***
George	2011		-0.247*			-0.296*		0.358**
Hughes	2010	0.373***						0.397***
Hughes	2011				0.452***			
Lambert	2010		-0.403***	-0.276*				
Lambert	2011		-0.496***					
Cave Spring	2010		-0.517***				-0.527*	
Cave Spring	2011			-0.284*				0.348**
Lowrey	2010				-0.257*			0.280**
Lowrey	2011	0.906***			0.227*			0.719***

Table A6 Mean values and standard deviations (±) of Cabernet franc berry composition variables. Bold values are mean values over the two year study period. Abbreviations: TA (titratable acidity).

	Cluster #	±	Berry Weight (g)	±	pH	±	Brix	±	TA (g/L)	±	Anthocyanins (mg/L)	±	Colour Intensity	±	Phenols (mg/L)	±
Buis	**31**	**7**	**1.51**	**0.163**	**3.54**	**0.07**	**23.7**	**1.2**	**6.10**	**0.42**	**620**	**123**	**15.7**	**3.7**	**1860**	**416**
2010	30	7	1.55	0.168	3.55	0.06	24.3	1.2	5.99	0.41	678	96	17.9	3.1	2023	384
2011	31	7	1.47	0.149	3.54	0.08	23.0	0.9	6.20	0.40	562	121	13.4	2.9	1697	383
George	**31**	**10**	**1.40**	**0.151**	**3.40**	**0.06**	**24.1**	**1.8**	**6.97**	**0.57**	**657**	**146**	**16.7**	**4.7**	**2230**	**359**
2010	23	4	1.47	0.129	3.43	0.06	24.5	1.4	6.66	0.39	765	110	20.3	3.6	2262	421
2011	40	7	1.33	0.136	3.37	0.05	23.6	2.1	7.28	0.56	550	85	13.0	2.2	2198	283
Kocsis	**20**	**7**	**1.39**	**0.295**	**3.57**	**0.09**	**23.8**	**1.8**	**6.24**	**0.37**	**654**	**127**	**18.3**	**5.2**	**2640**	**469**
2010	16	4	1.57	0.203	3.55	0.09	25.1	1.2	6.09	0.26	744	92	22.4	3.3	2798	507
2011	24	7	1.18	0.243	3.59	0.09	22.4	1.2	6.41	0.40	552	73	13.7	2.0	2460	345
Lambert	**35**	**9**	**1.32**	**0.102**	**3.50**	**0.05**	**22.4**	**1.3**	**7.24**	**0.43**	**617**	**97**	**16.0**	**2.2**	**2246**	**385**
2011	35	9	1.32	0.102	3.50	0.05	22.4	1.3	7.24	0.43	617	97	16.0	2.2	2246	385
Cave Spring	**32**	**9**	**1.42**	**0.166**	**3.41**	**0.07**	**24.1**	**1.5**	**6.82**	**0.60**	**713**	**88**	**17.4**	**2.7**	**2503**	**400**
2010	27	7	1.53	0.155	3.41	0.08	24.6	0.8	6.75	0.71	718	85	18.5	2.7	2499	350
2011	38	8	1.31	0.076	3.42	0.07	23.6	1.8	6.89	0.47	707	91	16.2	2.1	2507	447
Lowrey	**30**	**7**	**1.32**	**0.133**	**3.49**	**0.07**	**24.5**	**1.9**	**5.66**	**0.49**	**814**	**98**	**20.9**	**4.3**	**2525**	**732**
2010	27	6	1.37	0.106	3.50	0.08	25.7	1.0	5.64	0.67	864	76	24.3	3.0	2736	918
2011	34	6	1.27	0.140	3.47	0.06	23.3	1.8	5.68	0.21	765	92	17.5	2.2	2314	380

Table A7 Mean values and standard deviations (±) of Riesling berry composition variables. Bold values are mean values over the two year study period.

	Cluster #	±	Berry weight (g)	±	pH	±	Brix	±	Titratable Acidity (g/L)	±	Monoterpenes (mg/kg)	±
Buis	**59**	**19**	**1.6**	**0.1**	**2.85**	**0.55**	**18.6**	**1.0**	**10.36**	**0.8**	**1.96**	**0.34**
2010	45	13	1.6	0.1	3.15	0.06	19.0	0.8	9.90	0.8	1.95	0.36
2011	72	14	1.5	0.1	2.54	0.65	18.2	1.0	10.83	0.6	1.98	0.33
George	**40**	**11**	**1.6**	**0.2**	**3.12**	**0.09**	**18.9**	**1.2**	**9.22**	**0.9**	**2.64**	**0.54**
2010	36	8	1.6	0.2	3.05	0.07	19.4	1.1	8.59	0.6	2.66	0.48
2011	44	12	1.6	0.2	3.19	0.05	18.5	1.2	9.92	0.6	2.62	0.62
Hughes	**59**	**10**	**1.5**	**0.2**	**3.24**	**0.10**	**19.5**	**1.0**	**9.50**	**1.4**	**3.23**	**0.69**
2010	57	8	1.5	0.2	3.27	0.07	19.9	1.0	8.36	1.0	3.69	0.60
2011	61	11	1.5	0.2	3.20	0.10	19.1	0.8	10.63	0.6	2.76	0.40
Lambert	**39**	**14**	**1.6**	**0.2**	**3.30**	**0.05**	**19.1**	**1.0**	**10.58**	**1.5**	**2.42**	**0.54**
2010	38	11	1.7	0.1	3.30	0.04	19.4	0.8	9.31	0.6	2.72	0.58
2011	40	17	1.5	0.1	3.29	0.06	18.8	1.1	11.87	0.9	2.12	0.28
Cave Spring	**33**	**14**	**1.7**	**0.2**	**3.16**	**0.17**	**19.3**	**1.0**	**9.90**	**1.0**	**2.23**	**0.65**
2010	24	10	1.8	0.2	3.28	0.05	19.6	1.0	9.52	0.9	2.55	0.67
2011	41	12	1.6	0.2	3.04	0.15	19.0	0.9	10.28	0.9	1.90	0.44
Lowrey	**47**	**9**	**1.2**	**0.2**	**3.24**	**0.06**	**19.8**	**0.9**	**7.51**	**0.7**	**2.85**	**0.75**
2010	44	8	1.3	0.1	3.25	0.06	19.9	0.9	6.96	0.5	3.37	0.61
2011	50	9	1.1	0.1	3.22	0.06	19.6	1.0	8.04	0.4	2.32	0.44

Table A8 Mean values and standard deviations (±) of vine size .

Cabernet franc						
Mean value	**Buis**	**George**	**Kocsis**	**Lambert**[z]	**Cave Spring**	**Lowrey**
2010	591 ± 182	461 ±127	196 ±171	196 ± 72	789 ± 250	577 ± 194
2011	686 ± 287	298 ± 102	265 ± 164	198 ± 45	774 ± 230	375 ± 164
2010-2011	639 ± 245	379 ± 141	231 ± 171	197 ± 59	781 ± 239	476 ± 206
Riesling						
Mean value	**Buis**[z]	**George**	**Hughes**	**Lambert**[z]	**Cave Spring**	**Lowrey**
2010	108 ± 23	512 ± 145	523 ± 226	120 ± 22	501 ± 157	426 ± 142
2011	153 ± 33	411 ± 127	162 ± 29[z]	103 ± 27	662 ± 171	322 ± 122
2010-2011	131 ± 36	461 ± 145	451 ± 249	111 ± 26	582 ± 183	374 ± 142

[z] These sites were mechanically pre-pruned prior to data collection.

Table A9 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Buis Cabernet franc, 2010. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Antho (Anthocyanin concentration), Colour (Colour intensity), Phenol (Phenolic concentration), and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry Weight	pH	Brix	TA	Antho	Colour	Phenol	Soil Moisture	LWP	Bud Survival	Vine size	Mean Bud LT50
Cluster #	**0**	**< 0.0001**	0.241	**0.003**	**< 0.0001**	0.562	0.086	**0.030**	0.790	0.361	0.103	0.641	0.092	0.304
Yield (kg)	**< 0.0001**	**0**	0.093	**0.047**	**< 0.0001**	0.457	**0.001**	**0.000**	0.142	0.637	0.091	0.737	**0.000**	0.554
Berry Weight	0.241	0.093	**0**	0.760	0.185	**0.012**	**0.023**	**0.005**	0.492	0.569	0.157	0.238	**0.004**	**0.047**
pH	**0.003**	**0.047**	0.760	**0**	0.062	0.371	0.092	0.141	0.496	0.403	0.784	0.288	0.333	0.902
Brix	**< 0.0001**	**< 0.0001**	0.185	0.062	**0**	0.807	**< 0.0001**	**< 0.0001**	**0.002**	0.765	0.286	0.092	0.640	0.458
TA	0.562	0.457	**0.012**	0.371	0.807	**0**	0.779	0.467	0.078	**0.012**	0.836	0.788	0.249	0.431
Antho	0.086	**0.001**	**0.023**	0.092	**< 0.0001**	0.779	**0**	**< 0.0001**	**< 0.0001**	0.054	0.850	0.439	0.638	0.851
Colour Intensity	**0.030**	**0.000**	**0.005**	0.141	**< 0.0001**	0.467	**< 0.0001**	**0**	**< 0.0001**	**0.033**	0.892	0.480	0.662	0.758
Phenol	0.790	0.142	0.492	0.496	**0.002**	0.078	**< 0.0001**	**< 0.0001**	**0**	0.122	0.927	0.235	0.889	0.990
Soil Moisture	0.361	0.637	0.569	0.403	0.765	**0.012**	0.054	**0.033**	0.122	**0**	0.664	0.175	0.310	0.639
LWP	0.103	0.091	0.157	0.784	0.286	0.836	0.850	0.892	0.927	0.664	**0**	0.842	0.917	0.876
Bud Survival	0.641	0.737	0.238	0.288	0.092	0.788	0.439	0.480	0.235	0.175	0.842	**0**	0.098	0.315
Vine size	0.092	**0.000**	**0.004**	0.333	0.640	0.249	0.638	0.662	0.889	0.310	0.917	0.098	**0**	0.520
Mean Bud LT50	0.304	0.554	**0.047**	0.902	0.458	0.431	0.851	0.758	0.990	0.639	0.876	0.315	0.520	**0**

Table A10 *p*-value correlation table for vine characteristics and winter variables for Buis Cabernet franc, 2010. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Bud Survival	Vine size	Mean Bud LT50
Soil Moisture	**0**	0.664	0.839	0.436	0.453	0.175	0.310	0.639
Leaf Water Potential	0.664	**0**	0.442	**0.044**	0.061	0.842	0.917	0.876
Dec Bud LT50	0.839	0.442	**0**	0.079	0.621	0.734	0.590	**0.000**
Jan Bud LT50	0.436	**0.044**	0.079	**0**	0.268	0.086	0.306	**0.002**
Feb Bud LT50	0.453	0.061	0.621	0.268	**0**	0.185	0.333	0.111
Bud Survival	0.175	0.842	0.734	0.086	0.185	**0**	0.098	0.315
Vine size	0.310	0.917	0.590	0.306	0.333	0.098	**0**	0.520
Mean Bud LT50	0.639	0.876	**0.000**	**0.002**	0.111	0.315	0.520	**0**

Table A11 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Buis Cabernet franc, 2011. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Antho (Anthocyanin concentration), Colour (Colour intensity), Phenol (Phenolic concentration), and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry weight	Brix	pH	TA	Antho	Colour	Phenol	Soil Moisture	LWP	Mean Bud LT50	Bud Survival	Vine size
Cluster #	**0**	**< 0.0001**	**0.027**	**0.008**	0.087	**0.044**	**0.009**	**0.033**	**0.034**	0.172	0.176	0.388	0.188	**< 0.0001**
Yield	**< 0.0001**	**0**	**0.001**	**0.001**	0.062	0.138	**0.000**	**0.001**	**0.001**	0.051	**0.042**	0.167	0.355	**< 0.0001**
Berry weight	**0.027**	**0.001**	**0**	**0.000**	**< 0.0001**	0.678	**< 0.0001**	**0.000**	0.282	0.202	0.501	0.976	0.247	**0.001**
Brix	**0.008**	**0.001**	**0.000**	**0**	**0.042**	0.898	**< 0.0001**	**< 0.0001**	**0.000**	0.221	0.339	0.935	0.093	0.501
pH	0.087	0.062	**< 0.0001**	**0.042**	**0**	**0.035**	**0.001**	**0.030**	0.272	**0.019**	0.582	0.358	0.519	**0.003**
TA	**0.044**	0.138	0.678	0.898	**0.035**	**0**	0.104	0.062	0.202	0.219	0.271	0.133	0.349	0.684
Antho	**0.009**	**0.000**	**< 0.0001**	**< 0.0001**	**0.001**	0.104	**0**	**< 0.0001**	**0.000**	0.244	0.238	0.980	0.409	0.399
Colour	**0.033**	**0.001**	**0.000**	**< 0.0001**	**0.030**	0.062	**< 0.0001**	**0**	**< 0.0001**	0.579	0.088	0.510	0.175	0.396
Phenol	**0.034**	**0.001**	0.282	**0.000**	0.272	0.202	**0.000**	**< 0.0001**	**0**	0.954	0.314	0.139	0.549	0.058
Soil Moisture	0.172	0.051	0.202	0.221	**0.019**	0.219	0.244	0.579	0.954	**0**	0.137	0.195	0.376	**0.040**
LWP	0.176	**0.042**	0.501	0.339	0.582	0.271	0.238	0.088	0.314	0.137	**0**	0.072	0.369	0.095
Mean Bud LT50	0.388	0.167	0.976	0.935	0.358	0.133	0.980	0.510	0.139	0.195	0.072	**0**	1.000	0.106
Bud Survival	0.188	0.355	0.247	0.093	0.519	0.349	0.409	0.175	0.549	0.376	0.369	1.000	**0**	0.682
Vine size	**< 0.0001**	**< 0.0001**	**0.001**	0.501	**0.003**	0.684	0.399	0.396	0.058	**0.040**	0.095	0.106	0.682	**0**

Table A12 *p*-value correlation table for vine characteristics and winter variables for Buis Cabernet franc, 2011. Bolded values are significant. Abbreviations: LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Mean Bud LT50	Bud Survival	Vine size
Soil Moisture	**0**	0.137	0.794	0.625	**0.007**	0.195	0.376	**0.040**
LWP	0.137	**0**	0.663	0.373	**0.011**	0.072	0.369	0.095
Dec Bud LT50	0.794	0.663	**0**	**0.016**	0.969	**0.001**	0.330	**0.017**
Jan Bud LT50	0.625	0.373	**0.016**	**0**	0.269	**< 0.0001**	0.968	0.661
Feb Bud LT50	**0.007**	**0.011**	0.969	0.269	**0**	**0.006**	0.324	0.487
Mean Bud LT50	0.195	0.072	**0.001**	**< 0.0001**	**0.006**	**0**	1.000	0.106
Bud Survival	0.376	0.369	0.330	0.968	0.324	1.000	**0**	0.682
Vine size	**0.040**	0.095	**0.017**	0.661	0.487	0.106	0.682	**0**

Table A13 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for George Cabernet franc, 2010. Bolded values are significant. Abbreviations: Cluster # (Cluster number), TA (titratable acidity), Antho (Anthocyanin concentration), Colour (Colour intensity), LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry Weight	pH	Brix	TA	Antho	Colour	Phenols	Soil Moisture	LWP	Vine size	Bud Survival	Mean Bud LT50
Cluster #	**0**	**< 0.0001**	0.545	0.288	0.170	**0.049**	0.183	0.282	0.342	0.642	0.153	**0.022**	0.314	0.923
Yield	**< 0.0001**	**0**	**< 0.0001**	0.835	**0.037**	0.404	**0.005**	**0.012**	0.238	0.058	0.934	0.569	0.067	0.811
Berry Weight	0.545	**< 0.0001**	**0**	**0.045**	**0.023**	0.674	**< 0.0001**	**< 0.0001**	0.349	0.131	**0.035**	**0.000**	**0.041**	0.456
pH	0.288	0.835	**0.045**	**0**	**0.000**	**0.001**	0.424	0.695	0.073	0.344	0.464	0.126	0.546	0.187
Brix	0.170	**0.037**	**0.023**	**0.000**	**0**	**0.002**	**< 0.0001**	**< 0.0001**	**0.001**	0.985	0.261	0.491	0.086	0.590
TA	**0.049**	0.404	0.674	**0.001**	**0.002**	**0**	0.052	0.099	0.069	0.560	0.496	0.718	0.782	0.454
Antho	0.183	**0.005**	**< 0.0001**	0.424	**< 0.0001**	0.052	**0**	**< 0.0001**	**0.000**	0.072	**0.005**	**0.013**	0.298	0.062
Colour	0.282	**0.012**	**< 0.0001**	0.695	**< 0.0001**	0.099	**< 0.0001**	**0**	**< 0.0001**	0.241	**0.004**	**0.012**	0.127	0.151
Phenol	0.342	0.238	0.349	0.073	**0.001**	0.069	**0.000**	**< 0.0001**	**0**	0.293	0.670	0.958	0.610	**0.024**
Soil Moisture	0.642	0.058	0.131	0.344	0.985	0.560	0.072	0.241	0.293	**0**	0.337	0.712	0.359	0.267
LWP	0.153	0.934	**0.035**	0.464	0.261	0.496	**0.005**	**0.004**	0.670	0.337	**0**	0.869	0.108	0.701
Vine size	**0.022**	0.569	**0.000**	0.126	0.491	0.718	**0.013**	**0.012**	0.958	0.712	0.869	**0**	0.418	0.918
Bud Survival	0.314	0.067	**0.041**	0.546	0.086	0.782	0.298	0.127	0.610	0.359	0.108	0.418	**0**	0.843
Mean Bud LT50	0.923	0.811	0.456	0.187	0.590	0.454	0.062	0.151	**0.024**	0.267	0.701	0.918	0.843	**0**

Table A14 *p*-value correlation table for vine characteristics and winter variables for George Cabernet franc, 2010. Bolded values are significant. Abbreviations: LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Vine size	Bud Survival	Mean Bud LT50	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50
Soil Moisture	**0**	0.337	0.712	0.359	0.267	0.276	0.561	0.283
LWP	0.337	**0**	0.869	0.108	0.701	0.482	0.817	0.465
Vine size	0.712	0.869	**0**	0.418	0.918	0.889	0.542	0.323
Bud Survival	0.359	0.108	0.418	**0**	0.843	0.949	0.696	0.893
Mean Bud LT50	0.267	0.701	0.918	0.843	**0**	**0.000**	**< 0.0001**	**< 0.0001**
Dec Bud LT50	0.276	0.482	0.889	0.949	**0.000**	**0**	0.228	**0.023**
Jan Bud LT50	0.561	0.817	0.542	0.696	**< 0.0001**	0.228	**0**	**0.024**
Feb Bud LT50	0.283	0.465	0.323	0.893	**< 0.0001**	**0.023**	**0.024**	**0**

Table A15 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for George Cabernet franc, 2011. Bolded values are significant. Abbreviations: Cluster # (Cluster number), TA (titratable acidity), Antho (Anthocyanin concentration), Colour (Colour intensity), LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry weight	Brix	pH	TA	Antho	Colour	Phenols	Soil Moisture	LWP	Mean Bud LT50	Bud Survival	Vine size
Cluster number	**0**	**< 0.0001**	0.320	0.239	0.327	0.596	0.735	0.750	0.755	0.173	0.662	0.853	0.337	0.735
Yield	**< 0.0001**	**0**	**< 0.0001**	**< 0.0001**	0.131	**0.040**	0.331	**0.000**	**< 0.0001**	0.944	0.141	0.516	0.657	0.888
Berry weight	0.320	**< 0.0001**	**0**	**0.005**	0.247	**0.008**	**0.050**	**0.001**	**< 0.0001**	0.156	0.522	0.577	0.620	0.518
Brix	0.239	**< 0.0001**	**0.005**	**0**	**< 0.0001**	**< 0.0001**	0.529	**< 0.0001**	**< 0.0001**	**0.002**	**0.016**	0.528	0.637	0.174
pH	0.327	0.131	0.247	**< 0.0001**	**0**	**0.001**	0.255	0.075	0.966	**0.000**	0.218	0.404	0.586	**0.044**
TA	0.596	**0.040**	**0.008**	**< 0.0001**	**0.001**	**0**	0.051	**0.000**	**0.030**	**0.049**	**< 0.0001**	0.514	0.377	**0.026**
Antho	0.735	0.331	**0.050**	0.529	0.255	0.051	**0**	**0.007**	**0.006**	0.332	**0.016**	0.223	0.910	0.784
Colour	0.750	**0.000**	**0.001**	**< 0.0001**	0.075	**0.000**	**0.007**	**0**	**< 0.0001**	**0.044**	0.259	0.481	0.663	0.237
Phenol	0.755	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.966	**0.030**	**0.006**	**< 0.0001**	**0**	0.386	0.076	0.618	0.284	0.540
Soil Moisture	0.173	0.944	0.156	**0.002**	**0.000**	**0.049**	0.332	**0.044**	0.386	**0**	0.092	0.361	0.695	0.774
LWP	0.662	0.141	0.522	**0.016**	0.218	**< 0.0001**	**0.016**	0.259	0.076	0.092	**0**	0.793	0.652	0.741
Mean Bud LT50	0.853	0.516	0.577	0.528	0.404	0.514	0.223	0.481	0.618	0.361	0.793	**0**	**0.041**	0.353
Bud Survival	0.337	0.657	0.620	0.637	0.586	0.377	0.910	0.663	0.284	0.695	0.652	**0.041**	**0**	0.158
Vine size	0.735	0.888	0.518	0.174	**0.044**	**0.026**	0.784	0.237	0.540	0.774	0.741	0.353	0.158	**0**

Table A16 *p*-value correlation table for vine characteristics and winter variables for George Cabernet franc, 2011. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Mean Bud LT50	Bud Survival	Vine size
Soil Moisture	**0**	0.092	0.389	0.204	0.583	0.361	0.695	0.774
LWP	0.092	**0**	0.925	0.356	0.359	0.793	0.652	0.741
Dec Bud LT50	0.389	0.925	**0**	0.806	0.234	0.103	0.793	0.580
Jan Bud LT50	0.204	0.356	0.806	**0**	0.572	**0.000**	0.180	0.659
Feb Bud LT50	0.583	0.359	0.234	0.572	**0**	**0.002**	**0.047**	0.358
Mean Bud LT50	0.361	0.793	0.103	**0.000**	**0.002**	**0**	**0.041**	0.353
Bud Survival	0.695	0.652	0.793	0.180	**0.047**	**0.041**	**0**	0.158
Vine size	0.774	0.741	0.580	0.659	0.358	0.353	0.158	**0**

Table A17 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Kocsis Cabernet franc, 2010. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Antho (Anthocyanins), Colour (Colour intensity), LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry Weight	p H	Brix	TA	Antho	Colour	Phenols	Soil Moisture	LWP	Vine size	Bud Survival	Mean Bud LT50
Cluster number	**0**	**< 0.0001**	**0.036**	0.546	0.428	0.783	0.867	0.170	**0.012**	0.086	0.092	**< 0.0001**	0.308	0.199
Yield	**< 0.0001**	**0**	**< 0.0001**	0.525	0.511	0.056	0.781	0.118	**< 0.0001**	**< 0.0001**	**0.029**	**< 0.0001**	0.329	0.940
Berry Weight	**0.036**	**< 0.0001**	**0**	0.725	0.440	**0.020**	0.244	0.858	**< 0.0001**	**< 0.0001**	**0.010**	**< 0.0001**	0.190	0.444
p H	0.546	0.525	0.725	**0**	0.246	**0.007**	0.169	0.080	0.358	0.548	0.395	0.765	0.723	0.827
Brix	0.428	0.511	0.440	0.246	**0**	0.736	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.002**	0.365	0.468	0.560	0.947
TA	0.783	0.056	**0.020**	**0.007**	0.736	**0**	0.597	0.391	0.873	0.322	**0.013**	0.079	0.576	0.741
Antho	0.867	0.781	0.244	0.169	**< 0.0001**	0.597	**0**	**< 0.0001**	**0.006**	**0.044**	0.608	0.864	0.764	0.343
Colour	0.170	0.118	0.858	0.080	**< 0.0001**	0.391	**< 0.0001**	**0**	**< 0.0001**	**0.002**	0.831	0.134	0.797	0.376
Phenol	**0.012**	**< 0.0001**	**< 0.0001**	0.358	**< 0.0001**	0.873	**0.006**	**< 0.0001**	**0**	**< 0.0001**	0.544	**0.003**	0.078	0.801
Soil Moisture	0.086	**< 0.0001**	**< 0.0001**	0.548	**0.002**	0.322	**0.044**	**0.002**	**< 0.0001**	**0**	0.716	**0.001**	0.812	0.573
LWP	0.092	**0.029**	**0.010**	0.395	0.365	**0.013**	0.608	0.831	0.544	0.716	**0**	**0.032**	0.952	0.645
Vine size	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.765	0.468	0.079	0.864	0.134	**0.003**	**0.001**	**0.032**	**0**	0.285	0.793
Bud Survival	0.308	0.329	0.190	0.723	0.560	0.576	0.764	0.797	0.078	0.812	0.952	0.285	**0**	0.598
Mean Bud LT50	0.199	0.940	0.444	0.827	0.947	0.741	0.343	0.376	0.801	0.573	0.645	0.793	0.598	**0**

Table A18 *p*-value correlation table for vine characteristics and winter variables for Kocsis Cabernet franc, 2010. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Vine size	Bud Survival	Mean Bud LT50
Soil Moisture	**0**	0.716	0.333	0.434	0.253	**0.001**	0.812	0.573
Leaf Water Potential	0.716	**0**	0.990	0.667	0.687	**0.032**	0.952	0.645
Dec Bud LT50	0.333	0.990	**0**	0.492	0.907	0.139	0.418	0.174
Jan Bud LT50	0.434	0.667	0.492	**0**	**0.010**	0.948	0.165	**0.000**
Feb Bud LT50	0.253	0.687	0.907	**0.010**	**0**	0.329	0.888	**< 0.0001**
Vine size	**0.001**	**0.032**	0.139	0.948	0.329	**0**	0.285	0.793
Bud Survival	0.812	0.952	0.418	0.165	0.888	0.285	**0**	0.598
Mean Bud LT50	0.573	0.645	0.174	**0.000**	**< 0.0001**	0.793	0.598	**0**

Table A19 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Kocsis Cabernet franc, 2011. Bolded values are significant. Abbreviations: Cluster # (Cluster number), TA (titratable acidity), Antho (Anthocyanins), Colour (Colour intensity), LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry weight	Brix	pH	TA	Antho	Colour	Phenols	Soil Moisture	Leaf water potential	Mean Bud LT50	Bud Survival	Vine size
Cluster number	**0**	**< 0.0001**	0.435	0.071	**0.031**	0.320	0.790	0.895	0.402	0.070	0.115	0.411	0.107	**< 0.0001**
Yield	**< 0.0001**	**0**	0.289	0.227	0.385	0.460	0.892	0.745	0.175	0.062	**0.019**	0.945	0.110	**< 0.0001**
Berry weight	0.435	0.289	**0**	0.169	**0.002**	0.405	0.920	0.572	0.055	0.620	0.204	0.180	0.181	**0.048**
Brix	0.071	0.227	0.169	**0**	0.545	0.074	**< 0.0001**	**< 0.0001**	**0.028**	**0.005**	0.229	0.693	0.299	0.170
pH	**0.031**	0.385	**0.002**	0.545	**0**	0.310	0.900	0.368	0.422	0.265	0.833	0.129	0.928	0.487
TA	0.320	0.460	0.405	0.074	0.310	**0**	0.073	0.244	0.702	0.867	0.461	0.365	0.711	0.150
Antho	0.790	0.892	0.920	**< 0.0001**	0.900	0.073	**0**	**< 0.0001**	**0.001**	0.077	0.941	0.390	0.689	0.994
Colour	0.895	0.745	0.572	**< 0.0001**	0.368	0.244	**< 0.0001**	**0**	**< 0.0001**	0.086	0.727	0.675	0.603	0.496
Phenol	0.402	0.175	0.055	**0.028**	0.422	0.702	**0.001**	**< 0.0001**	**0**	0.467	0.251	0.770	0.502	0.065
Soil Moisture	0.070	0.062	0.620	**0.005**	0.265	0.867	0.077	0.086	0.467	**0**	0.652	0.717	0.086	**0.037**
LWP	0.115	**0.019**	0.204	0.229	0.833	0.461	0.941	0.727	0.251	0.652	**0**	0.124	0.416	**0.042**
Mean Bud LT50	0.411	0.945	0.180	0.693	0.129	0.365	0.390	0.675	0.770	0.717	0.124	**0**	**0.035**	0.473
Bud Survival	0.107	0.110	0.181	0.299	0.928	0.711	0.689	0.603	0.502	0.086	0.416	**0.035**	**0**	0.846
Vine size	**< 0.0001**	**< 0.0001**	**0.048**	0.170	0.487	0.150	0.994	0.496	0.065	**0.037**	**0.042**	0.473	0.846	**0**

Table A20 *p*-value correlation table for vine characteristics and winter variables for Kocsis Cabernet franc, 2011. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	December Bud LT50	Jan BudLT50	Feb Bud LT50	Mean Bud LT50	Bud Survival	Vine size
Soil Moisture	**0**	0.652	0.318	0.570	0.283	0.717	0.086	**0.037**
LWP	0.652	**0**	0.557	0.234	0.928	0.124	0.416	**0.042**
December Bud LT50	0.318	0.557	**0**	0.254	0.769	**0.005**	0.381	0.754
Jan BudLT50	0.570	0.234	0.254	**0**	0.466	**0.021**	0.713	**0.028**
Feb Bud LT50	0.283	0.928	0.769	0.466	**0**	**0.028**	0.095	**0.014**
Mean Bud LT50	0.717	0.124	**0.005**	**0.021**	**0.028**	**0**	**0.035**	0.473
Bud Survival	0.086	0.416	0.381	0.713	0.095	**0.035**	**0**	0.846
Vine size	**0.037**	**0.042**	0.754	**0.028**	**0.014**	0.473	0.846	**0**

Table A21 *p*-value correlation table for vine characteristics and winter variables for Lambert Cabernet franc, 2010. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Bud Survival	Vine size	Mean Bud LT50
Soil Moisture	**0**	0.850	0.715	0.331	0.627	0.537	0.636	0.553
Leaf Water Potential	0.850	**0**	0.891	0.862	0.698	0.176	0.937	0.931
Dec Bud LT50	0.715	0.891	**0**	0.283	**0.031**	0.580	0.470	**0.000**
Jan Bud LT50	0.331	0.862	0.283	**0**	0.058	0.610	0.422	**< 0.0001**
Feb Bud LT50	0.627	0.698	**0.031**	0.058	**0**	0.083	**0.045**	**< 0.0001**
Bud Survival	0.537	0.176	0.580	0.610	0.083	**0**	0.328	0.244
Vine size	0.636	0.937	0.470	0.422	**0.045**	0.328	**0**	0.913
Mean Bud LT50	0.553	0.931	**0.000**	**< 0.0001**	**< 0.0001**	0.244	0.913	**0**

Table A22 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Lambert Cabernet franc, 2011. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Antho (Anthocyanin concentration), Colour (Colour intensity), Phenol (Phenolic concentration), and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry weight	Brix	pH	TA	Antho	Colour	Phenol	Soil Moisture	LWP	Mean Bud LT50	Bud Survival	Vine size
Cluster #	**0**	**< 0.0001**	**0.006**	**0.023**	**0.031**	0.819	0.596	0.840	0.073	0.666	0.299	0.924	0.713	0.563
Yield	**< 0.0001**	**0**	0.181	**0.033**	0.416	0.535	0.126	0.159	**0.034**	0.577	0.719	0.779	0.370	0.979
Berry weight	**0.006**	0.181	**0**	**0.011**	0.176	0.590	0.280	0.678	0.052	0.787	**0.025**	0.238	0.332	0.955
Brix	**0.023**	**0.033**	**0.011**	**0**	**< 0.0001**	**0.007**	**< 0.0001**	**< 0.0001**	**0.001**	0.823	0.869	0.341	0.589	0.375
pH	**0.031**	0.416	0.176	**< 0.0001**	**0**	**< 0.0001**	0.572	0.248	**0.001**	0.794	0.425	0.840	**0.030**	0.317
TA	0.819	0.535	0.590	**0.007**	**< 0.0001**	**0**	0.472	0.293	0.118	0.694	0.215	0.898	0.185	0.051
Antho	0.596	0.126	0.280	**< 0.0001**	0.572	0.472	**0**	**< 0.0001**	**< 0.0001**	0.706	0.989	0.362	0.351	0.358
Colour	0.840	0.159	0.678	**< 0.0001**	0.248	0.293	**< 0.0001**	**0**	**< 0.0001**	0.735	0.361	0.053	0.815	0.535
Phenol	0.073	**0.034**	0.052	**0.001**	**0.001**	0.118	**< 0.0001**	**< 0.0001**	**0**	0.050	0.282	0.544	0.882	0.170
Soil Moisture	0.666	0.577	0.787	0.823	0.794	0.694	0.706	0.735	0.050	**0**	0.620	0.433	0.956	0.072
LWP	0.299	0.719	**0.025**	0.869	0.425	0.215	0.989	0.361	0.282	0.620	**0**	0.838	0.478	0.992
Mean Bud LT50	0.924	0.779	0.238	0.341	0.840	0.898	0.362	0.053	0.544	0.433	0.838	**0**	0.441	0.684
Bud Survival	0.713	0.370	0.332	0.589	**0.030**	0.185	0.351	0.815	0.882	0.956	0.478	0.441	**0**	0.569
Vine size (g)	0.563	0.979	0.955	0.375	0.317	0.051	0.358	0.535	0.170	0.072	0.992	0.684	0.569	**0**

Table A23 *p*-value correlation table for vine characteristics and winter variables for Lambert Cabernet franc, 2011. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	Jan BudLT50	Feb Bud LT50	Mean Bud LT50	Bud Survival	Vine size
Soil Moisture	**0**	0.620	0.161	0.740	0.893	0.433	0.956	0.072
Leaf water potential	0.620	**0**	0.756	0.394	0.895	0.838	0.478	0.992
Dec Bud LT50	0.161	0.756	**0**	0.079	0.971	**0.001**	0.920	0.343
Jan BudLT50	0.740	0.394	0.079	**0**	0.651	**< 0.0001**	0.121	0.113
Feb Bud LT50	0.893	0.895	0.971	0.651	**0**	**0.009**	0.908	0.086
Mean Bud LT50	0.433	0.838	**0.001**	**< 0.0001**	**0.009**	**0**	0.441	0.684
Bud Survival	0.956	0.478	0.920	0.121	0.908	0.441	**0**	0.569
Vine size	0.072	0.992	0.343	0.113	0.086	0.684	0.569	**0**

Table A24 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Cave Spring Cabernet franc, 2010. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Antho (Anthocyanin concentration), Colour (Colour intensity), Phenol (Phenolic concentration), and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry Weight	pH	Brix	TA	Antho	Colour	Phenol	Soil Moisture	LWP	Vine size	Bud Survival	Mean Bud LT50
Cluster #	**0**	**< 0.0001**	**< 0.0001**	0.464	0.405	0.091	**0.019**	**0.011**	0.271	**0.027**	0.708	0.932	0.458	0.263
Yield	**< 0.0001**	**0**	**0.000**	0.702	0.135	0.125	**0.001**	**< 0.0001**	**0.041**	**0.004**	0.931	0.080	0.500	0.454
Berry Weight	**< 0.0001**	**0.000**	**0**	0.872	0.197	0.475	0.316	0.425	0.976	**0.001**	0.318	0.392	0.213	0.074
pH	0.464	0.702	0.872	**0**	0.979	0.534	0.769	0.504	0.301	0.236	0.835	0.675	0.869	0.921
Brix	0.405	0.135	0.197	0.979	**0**	0.787	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.199	0.145	0.530	0.299	0.991
TA	0.091	0.125	0.475	0.534	0.787	**0**	0.195	0.182	0.526	0.125	0.362	0.625	0.474	0.715
Antho	**0.019**	**0.001**	0.316	0.769	**< 0.0001**	0.195	**0**	**< 0.0001**	**< 0.0001**	0.678	0.366	**0.043**	0.775	0.415
Colour	**0.011**	**< 0.0001**	0.425	0.504	**< 0.0001**	0.182	**< 0.0001**	**0**	**< 0.0001**	0.950	0.407	**0.041**	0.742	0.337
Phenol	0.271	**0.041**	0.976	0.301	**< 0.0001**	0.526	**< 0.0001**	**< 0.0001**	**0**	0.855	0.535	0.106	0.251	0.258
Soil Moisture	**0.027**	**0.004**	**0.001**	0.236	0.199	0.125	0.678	0.950	0.855	**0**	0.143	0.775	0.817	0.257
LWP	0.708	0.931	0.318	0.835	0.145	0.362	0.366	0.407	0.535	0.143	**0**	**0.009**	0.489	0.139
Vine size	0.932	0.080	0.392	0.675	0.530	0.625	**0.043**	**0.041**	0.106	0.775	**0.009**	**0**	0.350	0.100
Bud Survival	0.458	0.500	0.213	0.869	0.299	0.474	0.775	0.742	0.251	0.817	0.489	0.350	**0**	0.996
Mean Bud LT50	0.263	0.454	0.074	0.921	0.991	0.715	0.415	0.337	0.258	0.257	0.139	0.100	0.996	**0**

Table A25 *p*-value correlation table for vine characteristics and winter variables for Cave Spring Cabernet franc, 2010. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Vine size	Bud Survival	Mean Bud LT50
Soil Moisture	**0**	0.143	0.469	0.384	0.174	0.775	0.817	0.257
Leaf Water Potential	0.143	**0**	**0.013**	0.330	0.555	**0.009**	0.489	0.139
Dec Bud LT50	0.469	**0.013**	**0**	**0.005**	**0.032**	**0.043**	0.538	**< 0.0001**
Jan Bud LT50	0.384	0.330	**0.005**	**0**	**0.011**	0.085	0.619	**< 0.0001**
Feb Bud LT50	0.174	0.555	**0.032**	**0.011**	**0**	0.584	0.979	**< 0.0001**
Vine size	0.775	**0.009**	**0.043**	0.085	0.584	**0**	0.350	0.100
Bud Survival	0.817	0.489	0.538	0.619	0.979	0.350	**0**	0.996
Mean Bud LT50	0.257	0.139	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.100	0.996	**0**

Table A26 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Cave Spring Cabernet franc, 2011. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Antho (Anthocyanin concentration), Colour (Colour intensity), Phenol (Phenolic concentration), and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry weight	Brix	pH	TA	Antho	Colour	Phenol	Soil moisture	LWP	Mean Bud LT50	Bud Survival	Vine size
Cluster #	**0**	**< 0.0001**	**0.018**	0.075	0.069	0.064	0.993	0.758	0.236	0.231	0.648	0.396	**0.036**	0.366
Yield	**< 0.0001**	**0**	**0.008**	**0.005**	0.067	**0.011**	0.678	0.134	0.114	0.714	0.495	0.200	0.421	**0.026**
Berry weight (g)	**0.018**	**0.008**	**0**	0.356	**0.005**	**0.009**	0.197	0.843	0.854	**0.000**	0.444	0.311	**0.013**	0.250
Brix	0.075	**0.005**	0.356	**0**	**0.020**	**0.027**	**0.000**	**< 0.0001**	**< 0.0001**	0.090	0.705	0.667	0.230	0.100
pH	0.069	0.067	**0.005**	**0.020**	**0**	**0.029**	0.133	0.057	0.104	0.312	0.127	0.422	**0.041**	0.462
TA	0.064	**0.011**	**0.009**	**0.027**	**0.029**	**0**	0.454	0.798	0.377	0.319	0.251	0.802	0.714	0.328
Antho	0.993	0.678	0.197	**0.000**	0.133	0.454	**0**	**< 0.0001**	**< 0.0001**	**0.009**	0.984	0.763	**0.036**	0.529
Colour	0.758	0.134	0.843	**< 0.0001**	0.057	0.798	**< 0.0001**	**0**	**< 0.0001**	**0.003**	0.515	0.813	0.061	0.961
Phenol	0.236	0.114	0.854	**< 0.0001**	0.104	0.377	**< 0.0001**	**< 0.0001**	**0**	**0.004**	0.853	0.866	0.202	0.697
Soil moisture	0.231	0.714	**0.000**	0.090	0.312	0.319	**0.009**	**0.003**	**0.004**	**0**	0.383	0.460	**0.003**	0.137
LWP	0.648	0.495	0.444	0.705	0.127	0.251	0.984	0.515	0.853	0.383	**0**	0.243	0.095	0.179
Mean Bud LT50	0.396	0.200	0.311	0.667	0.422	0.802	0.763	0.813	0.866	0.460	0.243	**0**	0.725	0.310
Bud Survival	**0.036**	0.421	**0.013**	0.230	**0.041**	0.714	**0.036**	0.061	0.202	**0.003**	0.095	0.725	**0**	0.478
Vine size	0.366	**0.026**	0.250	0.100	0.462	0.328	0.529	0.961	0.697	0.137	0.179	0.310	0.478	**0**

Table A27 *p*-value correlation table for vine characteristics and winter variables for Cave Spring Cabernet franc, 2011. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Mean Bud LT50	Bud Survival	Vine size
Soil moisture	**0**	0.383	0.264	0.880	0.417	0.460	**0.003**	0.137
Leaf Water Potential	0.383	**0**	0.684	**0.006**	0.613	0.243	0.095	0.179
Dec Bud LT50	0.264	0.684	**0**	0.402	**0.048**	**0.001**	0.497	0.790
Jan Bud LT50	0.880	**0.006**	0.402	**0**	0.155	**0.002**	0.161	**0.037**
Feb Bud LT50	0.417	0.613	**0.048**	0.155	**0**	**0.000**	0.970	0.991
Mean Bud LT50	0.460	0.243	**0.001**	**0.002**	**0.000**	**0**	0.725	0.310
Bud Survival	**0.003**	0.095	0.497	0.161	0.970	0.725	**0**	0.478
Vine size	0.137	0.179	0.790	**0.037**	0.991	0.310	0.478	**0**

Table A28 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Lowrey Cabernet franc, 2010. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Antho (Anthocyanin concentration), Colour (Colour intensity), Phenol (Phenolic concentration), and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry Weight	pH	Brix	TA	Antho	Colour	Phenol	Soil Moisture	LWP	Bud Survival	Vine size	Mean Bud LT50
Cluster #	**0**	**< 0.0001**	**0.015**	**< 0.0001**	**0.002**	0.076	0.241	0.143	**0.001**	0.911	0.124	0.634	0.223	0.781
Yield	**< 0.0001**	**0**	**0.000**	**0.001**	**< 0.0001**	**0.036**	**0.021**	**0.012**	**0.004**	0.183	**0.024**	0.100	0.396	0.979
Berry Weight	**0.015**	**0.000**	**0**	0.132	**0.014**	**0.001**	**< 0.0001**	**< 0.0001**	**0.015**	0.660	0.993	0.140	0.088	0.148
pH	**< 0.0001**	**0.001**	0.132	**0**	**0.001**	0.810	0.432	0.808	**0.001**	0.792	**0.021**	0.110	**0.023**	0.308
Brix	**0.002**	**< 0.0001**	**0.014**	**0.001**	**0**	**0.026**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.022**	0.199	0.340	0.246	0.802
TA	0.076	**0.036**	**0.001**	0.810	**0.026**	**0**	**0.030**	**0.026**	0.120	0.938	0.351	0.429	0.878	**0.041**
Antho	0.241	**0.021**	**< 0.0001**	0.432	**< 0.0001**	**0.030**	**0**	**< 0.0001**	**0.000**	0.706	0.474	0.054	0.512	0.805
Colour	0.143	**0.012**	**< 0.0001**	0.808	**< 0.0001**	**0.026**	**< 0.0001**	**0**	**< 0.0001**	0.568	0.921	0.243	0.798	0.520
Phenol	**0.001**	**0.004**	**0.015**	**0.001**	**< 0.0001**	0.120	**0.000**	**< 0.0001**	**0**	**< 0.0001**	0.886	0.862	0.415	0.487
Soil Moisture	0.911	0.183	0.660	0.792	**0.022**	0.938	0.706	0.568	**< 0.0001**	**0**	0.551	0.267	0.094	0.288
LWP	0.124	**0.024**	0.993	**0.021**	0.199	0.351	0.474	0.921	0.886	0.551	**0**	0.551	**< 0.0001**	0.095
Bud Survival	0.634	0.100	0.140	0.110	0.340	0.429	0.054	0.243	0.862	0.267	0.551	**0**	0.496	0.904
Vine size	0.223	0.396	0.088	**0.023**	0.246	0.878	0.512	0.798	0.415	0.094	**< 0.0001**	0.496	**0**	0.305
Mean Bud LT50	0.781	0.979	0.148	0.308	0.802	**0.041**	0.805	0.520	0.487	0.288	0.095	0.904	0.305	**0**

Table A29 *p*-value correlation table for vine characteristics and winter variables for Lowrey Cabernet franc, 2010. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Bud Survival	Vine size	Mean Bud LT50	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50
Soil Moisture	**0**	0.551	0.267	0.094	0.288	0.983	0.267	0.473
LWP	0.551	**0**	0.551	**< 0.0001**	0.095	0.276	0.217	0.360
Bud Survival	0.267	0.551	**0**	0.496	0.904	0.142	0.816	0.123
Vine size	0.094	**< 0.0001**	0.496	**0**	0.305	0.661	0.537	0.140
Mean Bud LT50	0.288	0.095	0.904	0.305	**0**	**0.005**	**< 0.0001**	**0.004**
Dec Bud LT50	0.983	0.276	0.142	0.661	**0.005**	**0**	0.243	0.940
Jan Bud LT50	0.267	0.217	0.816	0.537	**< 0.0001**	0.243	**0**	0.152
Feb Bud LT50	0.473	0.360	0.123	0.140	**0.004**	0.940	0.152	**0**

Table A30 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Lowrey Cabernet franc, 2011. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Antho (Anthocyanin concentration), Colour (Colour intensity), Phenol (Phenolic concentration), and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry weight	Brix	pH	TA	Antho	Colour	Phenol	Soil Moisture	LWP	Mean Bud LT50	Bud Survival	Vine size
Cluster number	**0**	**< 0.0001**	0.106	**0.002**	0.554	0.299	**0.036**	**0.001**	**0.001**	0.095	0.318	0.317	0.186	**0.026**
Yield	**< 0.0001**	**0**	**< 0.0001**	**< 0.0001**	0.638	0.957	**< 0.0001**	**< 0.0001**	**0.001**	0.305	0.199	0.894	0.482	**0.002**
Berry weight	0.106	**< 0.0001**	**0**	**< 0.0001**	0.258	0.071	0.052	**0.006**	0.285	0.744	0.476	0.193	0.929	**< 0.0001**
Brix	**0.002**	**< 0.0001**	**< 0.0001**	**0**	**0.017**	0.053	**< 0.0001**	**< 0.0001**	**0.001**	0.932	0.965	0.965	0.797	0.833
pH	0.554	0.638	0.258	**0.017**	**0**	0.567	0.124	0.352	0.081	0.820	0.103	0.177	0.834	0.378
TA	0.299	0.957	0.071	0.053	0.567	**0**	0.759	0.442	0.342	0.269	**0.015**	0.075	0.620	0.996
Antho	**0.036**	**< 0.0001**	0.052	**< 0.0001**	0.124	0.759	**0**	**< 0.0001**	**< 0.0001**	0.197	0.775	0.964	0.789	**0.001**
Colour	**0.001**	**< 0.0001**	**0.006**	**< 0.0001**	0.352	0.442	**< 0.0001**	**0**	**< 0.0001**	0.963	0.683	0.903	0.274	**0.045**
Phenol	**0.001**	**0.001**	0.285	**0.001**	0.081	0.342	**< 0.0001**	**< 0.0001**	**0**	0.312	0.594	0.271	0.149	0.571
Soil Moisture	0.095	0.305	0.744	0.932	0.820	0.269	0.197	0.963	0.312	**0**	0.355	0.846	0.367	0.791
LWP	0.318	0.199	0.476	0.965	0.103	**0.015**	0.775	0.683	0.594	0.355	**0**	0.137	0.314	**0.040**
Mean Bud LT50	0.317	0.894	0.193	0.965	0.177	0.075	0.964	0.903	0.271	0.846	0.137	**0**	0.792	0.209
Bud Survival	0.186	0.482	0.929	0.797	0.834	0.620	0.789	0.274	0.149	0.367	0.314	0.792	**0**	0.176
Vine size	**0.026**	**0.002**	**< 0.0001**	0.833	0.378	0.996	**0.001**	**0.045**	0.571	0.791	**0.040**	0.209	0.176	**0**

Table A31 *p*-value correlation table for vine characteristics and winter variables for Lowrey Cabernet franc, 2011. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Mean Bud LT50	Bud Survival	Vine size
Soil Moisture	**0**	0.355	0.381	0.765	0.893	0.846	0.367	0.791
Leaf water potential	0.355	**0**	0.722	0.259	0.333	0.137	0.314	**0.040**
Dec Bud LT50	0.381	0.722	**0**	0.678	0.593	0.525	0.535	0.259
Jan Bud LT50	0.765	0.259	0.678	**0**	0.954	**< 0.0001**	0.918	0.362
Feb Bud LT50	0.893	0.333	0.593	0.954	**0**	**0.016**	0.475	0.367
Mean Bud LT50	0.846	0.137	0.525	**< 0.0001**	**0.016**	**0**	0.792	0.209
Bud Survival	0.367	0.314	0.535	0.918	0.475	0.792	**0**	0.176
Vine size	0.791	**0.040**	0.259	0.362	0.367	0.209	0.176	**0**

Table A32 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Buis Riesling, 2010. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Terpene (Monoterpene concentration) and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry weight	pH	Brix	TA	Terpene	Soil Moisture	LWP	Bud Survival	Vine size	Mean Bud LT50
Cluster #	**0**	**< 0.0001**	0.518	**0.006**	0.204	0.297	0.638	0.597	0.129	0.117	0.951	0.829
Yield	**< 0.0001**	**0**	**0.030**	0.060	**< 0.0001**	**0.008**	0.267	0.603	0.662	0.130	0.772	0.432
Berry weight	0.518	**0.030**	**0**	0.549	**0.001**	0.659	0.801	0.165	0.431	0.252	0.352	0.994
pH	**0.006**	0.060	0.549	**0**	0.082	0.521	**0.001**	0.796	0.794	0.409	0.619	0.701
Brix	0.204	**< 0.0001**	**0.001**	0.082	**0**	0.109	0.122	0.436	0.567	0.470	0.790	0.382
TA	0.297	**0.008**	0.659	0.521	0.109	**0**	0.199	0.739	0.097	0.999	0.095	0.568
Terpene	0.638	0.267	0.801	**0.001**	0.122	0.199	**0**	0.286	0.848	0.105	0.057	0.912
Soil Moisture	0.597	0.603	0.165	0.796	0.436	0.739	0.286	**0**	0.434	0.940	0.054	0.399
Leaf Water Potential	0.129	0.662	0.431	0.794	0.567	0.097	0.848	0.434	**0**	0.421	0.557	0.358
Bud Survival	0.117	0.130	0.252	0.409	0.470	0.999	0.105	0.940	0.421	**0**	0.732	0.353
Vine size	0.951	0.772	0.352	0.619	0.790	0.095	0.057	0.054	0.557	0.732	**0**	0.680
Mean Bud LT50	0.829	0.432	0.994	0.701	0.382	0.568	0.912	0.399	0.358	0.353	0.680	**0**

Table A33 *p*-value correlation table for vine characteristics and winter variables for Buis Riesling, 2010. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Bud Survival	Vine size	Mean Bud LT50
Soil Moisture	**0**	0.434	0.385	0.134	0.636	0.940	0.054	0.399
Leaf Water Potential	0.434	**0**	0.201	0.253	0.248	0.421	0.557	0.358
Dec Bud LT50	0.385	0.201	**0**	0.127	0.100	**0.005**	0.730	**< 0.0001**
Jan Bud LT50	0.134	0.253	0.127	**0**	0.922	0.580	0.174	**0.005**
Feb Bud LT50	0.636	0.248	0.100	0.922	**0**	0.504	0.317	**0.002**
Bud Survival	0.940	0.421	**0.005**	0.580	0.504	**0**	0.732	0.353
Vine size	0.054	0.557	0.730	0.174	0.317	0.732	**0**	0.680
Mean Bud LT50	0.399	0.358	**< 0.0001**	**0.005**	**0.002**	0.353	0.680	**0**

Table A34 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Buis Riesling, 2011. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Terpene (Monoterpene concentration) and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry weight	Brix	pH	TA	Terpene	Soil Moisture	LWP	Mean Bud LT50	Bud Survival	Vine size
Cluster number	**0**	**< 0.0001**	**0.023**	0.144	0.779	0.448	0.486	0.793	0.902	0.178	0.600	0.584
Yield	**< 0.0001**	**0**	0.527	**0.004**	0.475	0.225	0.079	0.991	0.240	0.094	0.436	0.582
Berry weight	**0.023**	0.527	**0**	0.469	0.497	0.960	0.931	0.073	0.822	0.092	0.089	0.411
Brix	0.144	**0.004**	0.469	**0**	0.439	0.096	**0.043**	0.104	0.867	**0.005**	0.889	0.189
pH	0.779	0.475	0.497	0.439	**0**	0.342	0.463	**0.001**	0.965	0.088	0.523	0.160
TA	0.448	0.225	0.960	0.096	0.342	**0**	0.699	0.987	0.228	0.486	0.634	0.434
Terpene	0.486	0.079	0.931	**0.043**	0.463	0.699	**0**	0.073	0.575	0.536	0.801	**0.025**
Soil Moisture	0.793	0.991	0.073	0.104	**0.001**	0.987	0.073	**0**	0.562	0.604	0.247	0.517
Leaf Water Potential	0.902	0.240	0.822	0.867	0.965	0.228	0.575	0.562	**0**	0.661	0.370	0.971
Mean Bud LT50	0.178	0.094	0.092	**0.005**	0.088	0.486	0.536	0.604	0.661	**0**	0.861	0.966
Bud Survival	0.600	0.436	0.089	0.889	0.523	0.634	0.801	0.247	0.370	0.861	**0**	0.449
Vine size	0.584	0.582	0.411	0.189	0.160	0.434	**0.025**	0.517	0.971	0.966	0.449	**0**

Table A35 *p*-value correlation table for vine characteristics and winter variables for Buis Riesling, 2011. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Mean Bud LT50	Bud Survival	Vine size
Soil Moisture	**0**	0.562	0.267	0.587	0.136	0.604	0.247	0.517
Leaf Water Potential	0.562	**0**	0.632	0.510	0.712	0.661	0.370	0.971
Dec Bud LT50	0.267	0.632	**0**	0.326	0.128	**< 0.0001**	0.877	0.410
Jan Bud LT50	0.587	0.510	0.326	**0**	0.181	**0.001**	0.303	0.804
Feb Bud LT50	0.136	0.712	0.128	0.181	**0**	**0.003**	0.484	0.487
Mean Bud LT50	0.604	0.661	**< 0.0001**	**0.001**	**0.003**	**0**	0.861	0.966
Bud Survival	0.247	0.370	0.877	0.303	0.484	0.861	**0**	0.449
Vine size	0.517	0.971	0.410	0.804	0.487	0.966	0.449	**0**

Table A36 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for George Riesling, 2010. Bolded values are significant. Abbreviations: Cluster # (Cluster number), TA (titratable acidity), Terpene (Monoterpene concentration) and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry Weight	pH	Brix	TA	Terpene	Soil Moisture	LWP	Vine size	Bud Survival	Mean Bud LT50
Cluster number	**0**	**< 0.0001**	0.323	0.126	**0.015**	0.748	0.942	0.196	0.957	**0.002**	0.392	0.878
Yield	**< 0.0001**	**0**	0.129	0.455	**0.016**	0.886	0.772	0.951	0.591	**< 0.0001**	0.839	0.671
Berry Weight	0.323	0.129	**0**	**0.007**	0.378	0.341	0.909	0.089	0.318	0.306	0.656	0.124
pH	0.126	0.455	**0.007**	**0**	**0.000**	0.051	0.266	**0.011**	0.467	0.161	0.416	0.576
Brix	**0.015**	**0.016**	0.378	**0.000**	**0**	**0.003**	0.281	0.721	0.424	0.237	0.890	0.588
TA	0.748	0.886	0.341	0.051	**0.003**	**0**	0.064	**0.025**	**0.008**	0.712	0.343	0.627
Terpene	0.942	0.772	0.909	0.266	0.281	0.064	**0**	0.392	**0.042**	0.935	0.053	0.497
Soil Moisture	0.196	0.951	0.089	**0.011**	0.721	**0.025**	0.392	**0**	**0.049**	0.583	0.082	0.613
Leaf Water Potential	0.957	0.591	0.318	0.467	0.424	**0.008**	**0.042**	**0.049**	**0**	0.861	0.088	0.472
Vine size	**0.002**	**< 0.0001**	0.306	0.161	0.237	0.712	0.935	0.583	0.861	**0**	0.901	0.398
Bud Survival	0.392	0.839	0.656	0.416	0.890	0.343	0.053	0.082	0.088	0.901	**0**	0.447
Mean Bud LT50	0.878	0.671	0.124	0.576	0.588	0.627	0.497	0.613	0.472	0.398	0.447	**0**

Table A37 *p*-value correlation table for vine characteristics and winter variables for George Riesling, 2010. Bolded values are significant. Abbreviations: LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Vine size	Bud Survival	Mean Bud LT50
Soil Moisture	**0**	**0.049**	0.226	0.442	0.177	0.583	0.082	0.613
Leaf Water Potential	**0.049**	**0**	0.432	0.922	0.456	0.861	0.088	0.472
Dec Bud LT50	0.226	0.432	**0**	**0.010**	0.190	0.819	0.910	**< 0.0001**
Jan Bud LT50	0.442	0.922	**0.010**	**0**	0.960	0.061	0.932	**0.001**
Feb Bud LT50	0.177	0.456	0.190	0.960	**0**	0.808	**0.019**	**0.011**
Vine size	0.583	0.861	0.819	0.061	0.808	**0**	0.901	0.398
Bud Survival	0.082	0.088	0.910	0.932	**0.019**	0.901	**0**	0.447
Mean Bud LT50	0.613	0.472	**< 0.0001**	**0.001**	**0.011**	0.398	0.447	**0**

Table A38 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for George Riesling, 2011. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Terpene (Monoterpene concentration) and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry weight	Brix	pH	TA	Terpene	Soil Moisture	LWP	Mean Bud LT50	Bud Survival	Vine size
Cluster #	**0**	**< 0.0001**	0.469	**0.045**	**0.018**	0.094	0.498	**0.036**	**0.045**	0.124	**0.037**	0.328
Yield	**< 0.0001**	**0**	0.583	0.105	**0.039**	0.615	0.310	**0.013**	0.385	0.352	0.320	**0.002**
Berry weight	0.469	0.583	**0**	**0.040**	0.386	0.195	0.326	0.563	**0.012**	0.999	0.515	0.611
Brix	**0.045**	0.105	**0.040**	**0**	**0.007**	**0.005**	0.066	**0.014**	0.219	0.087	**0.047**	0.300
pH	**0.018**	**0.039**	0.386	**0.007**	**0**	**0.001**	0.106	0.059	0.152	0.105	0.427	0.068
TA	0.094	0.615	0.195	**0.005**	**0.001**	**0**	**0.004**	**0.026**	**0.024**	0.993	0.721	0.445
Terpene	0.498	0.310	0.326	0.066	0.106	**0.004**	**0**	0.356	**0.011**	0.877	0.710	0.504
Soil Moisture	**0.036**	**0.013**	0.563	**0.014**	0.059	**0.026**	0.356	**0**	0.152	0.792	0.325	0.616
LWP	**0.045**	0.385	**0.012**	0.219	0.152	**0.024**	**0.011**	0.152	**0**	0.254	0.412	0.691
Mean Bud LT50	0.124	0.352	0.999	0.087	0.105	0.993	0.877	0.792	0.254	**0**	**0.011**	0.909
Bud Survival	**0.037**	0.320	0.515	**0.047**	0.427	0.721	0.710	0.325	0.412	**0.011**	**0**	0.798
Vine size	0.328	**0.002**	0.611	0.300	0.068	0.445	0.504	0.616	0.691	0.909	0.798	**0**

Table A39 *p*-value correlation table for vine characteristics and winter variables for George Riesling, 2011. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Mean Bud LT50	Bud Survival	Vine size
Soil Moisture	**0**	0.152	0.323	0.910	0.922	0.792	0.325	0.616
Leaf water potential	0.152	**0**	1.000	0.213	0.991	0.254	0.412	0.691
Dec Bud LT50	0.323	1.000	**0**	0.205	**0.047**	0.384	**0.042**	0.713
Jan Bud LT50	0.910	0.213	0.205	**0**	0.562	**0.003**	**0.042**	0.741
Feb Bud LT50	0.922	0.991	**0.047**	0.562	**0**	**0.019**	0.672	0.758
Mean Bud LT50	0.792	0.254	0.384	**0.003**	**0.019**	**0**	**0.011**	0.909
Bud Survival	0.325	0.412	**0.042**	**0.042**	0.672	**0.011**	**0**	0.798
Vine size	0.616	0.691	0.713	0.741	0.758	0.909	0.798	**0**

Table A40 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Hughes Riesling, 2010. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Terpene (Monoterpene concentration) and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry Weight	pH	Brix	TA	Terpene	Soil Moisture	LWP	Bud Survival	Vine size	Mean Bud LT50
Cluster #	**0**	**0.000**	0.224	**0.017**	**0.028**	0.849	**0.008**	0.115	0.383	0.449	0.818	0.403
Yield	**0.000**	**0**	**0.001**	0.206	0.813	0.091	0.658	0.932	0.765	0.776	**0.001**	0.170
Berry Weight	0.224	**0.001**	**0**	0.073	**0.009**	0.354	0.733	0.388	**0.002**	**0.030**	**< 0.0001**	0.494
pH	**0.017**	0.206	0.073	**0**	**0.000**	0.199	0.489	0.883	0.182	**0.048**	**0.047**	**0.046**
Brix	**0.028**	0.813	**0.009**	**0.000**	**0**	0.455	0.463	0.805	0.649	0.196	**0.004**	0.950
TA	0.849	0.091	0.354	0.199	0.455	**0**	0.653	0.137	0.907	0.409	0.117	0.894
Terpene	**0.008**	0.658	0.733	0.489	0.463	0.653	**0**	0.409	0.802	0.292	0.941	0.423
Soil Moisture	0.115	0.932	0.388	0.883	0.805	0.137	0.409	**0**	0.052	**0.036**	0.186	0.881
LWP	0.383	0.765	**0.002**	0.182	0.649	0.907	0.802	0.052	**0**	**0.004**	**0.003**	0.506
Bud Survival	0.449	0.776	**0.030**	**0.048**	0.196	0.409	0.292	**0.036**	**0.004**	**0**	0.176	0.974
Vine size	0.818	**0.001**	**< 0.0001**	**0.047**	**0.004**	0.117	0.941	0.186	**0.003**	0.176	**0**	0.717
Mean Bud LT50	0.403	0.170	0.494	**0.046**	0.950	0.894	0.423	0.881	0.506	0.974	0.717	**0**

Table A41 *p*-value correlation table for vine characteristics and winter variables for Hughes Riesling, 2010. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Bud Survival	Vine size	Mean Bud LT50
Soil Moisture	**0**	0.052	0.540	0.920	0.678	**0.036**	0.186	0.881
LWP	0.052	**0**	0.564	0.662	0.820	**0.004**	**0.003**	0.506
Dec Bud LT50	0.540	0.564	**0**	0.181	0.698	0.413	0.269	0.072
Jan Bud LT50	0.920	0.662	0.181	**0**	0.587	0.500	0.466	0.073
Feb Bud LT50	0.678	0.820	0.698	0.587	**0**	0.951	0.868	**< 0.0001**
Bud Survival	**0.036**	**0.004**	0.413	0.500	0.951	**0**	0.176	0.974
Vine size	0.186	**0.003**	0.269	0.466	0.868	0.176	**0**	0.717
Mean Bud LT50	0.881	0.506	0.072	0.073	**< 0.0001**	0.974	0.717	**0**

Table A42 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Hughes Riesling, 2011. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Terpene (Monoterpene concentration) and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry weight	Brix	pH	TA	Terpene	Soil Moisture	LWP	Mean Bud LT50	Bud Survival	Vine size
Cluster #	**0**	**< 0.0001**	**0.000**	0.708	0.889	0.237	0.888	0.057	**0.026**	0.743	0.638	0.355
Yield	**< 0.0001**	**0**	0.274	0.417	0.836	**< 0.0001**	0.134	0.282	0.896	0.523	0.662	0.418
Berry weight	**0.000**	0.274	**0**	**0.007**	0.149	0.075	**0.042**	0.386	**0.000**	0.757	0.133	0.236
Brix	0.708	0.417	**0.007**	**0**	0.939	0.239	**0.008**	0.590	0.817	0.235	**0.043**	0.367
pH	0.889	0.836	0.149	0.939	**0**	0.236	0.616	0.622	0.244	0.655	0.053	**0.008**
TA	0.237	**< 0.0001**	0.075	0.239	0.236	**0**	0.066	0.399	0.792	0.651	0.369	0.923
Terpene	0.888	0.134	**0.042**	**0.008**	0.616	0.066	**0**	0.101	**0.016**	0.569	0.110	0.421
Soil Moisture	0.057	0.282	0.386	0.590	0.622	0.399	0.101	**0**	**0.001**	0.965	0.243	0.379
LWP	**0.026**	0.896	**0.000**	0.817	0.244	0.792	**0.016**	**0.001**	**0**	0.842	0.085	0.370
Mean Bud LT50	0.743	0.523	0.757	0.235	0.655	0.651	0.569	0.965	0.842	**0**	0.069	0.693
Bud Survival	0.638	0.662	0.133	**0.043**	0.053	0.369	0.110	0.243	0.085	0.069	**0**	0.149
Vine size	0.355	0.418	0.236	0.367	**0.008**	0.923	0.421	0.379	0.370	0.693	0.149	**0**

Table A43 *p*-value correlation table for vine characteristics and winter variables for Hughes Riesling, 2011. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Mean Bud LT50	Bud Survival	Vine size
Soil Moisture	**0**	**0.001**	0.821	0.414	0.432	0.965	0.243	0.379
Leaf water potential	**0.001**	**0**	0.631	0.258	0.410	0.842	0.085	0.370
Dec Bud LT50	0.821	0.631	**0**	0.742	**0.046**	**0.000**	0.061	0.882
Jan Bud LT50	0.414	0.258	0.742	**0**	0.647	0.144	0.866	0.903
Feb Bud LT50	0.432	0.410	**0.046**	0.647	**0**	**< 0.0001**	**0.009**	0.174
Mean Bud LT50	0.965	0.842	**0.000**	0.144	**< 0.0001**	**0**	0.069	0.693
Bud Survival	0.243	0.085	0.061	0.866	**0.009**	0.069	**0**	0.149
Vine size	0.379	0.370	0.882	0.903	0.174	0.693	0.149	**0**

Table A44 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Lambert Riesling, 2010. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Terpene (Monoterpene concentration) and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry Weight	pH	Brix	TA	Terpene	Soil Moisture	LWP	Bud Survival	Mean Bud LT50	Vine size
Cluster #	**0**	**< 0.0001**	**0.000**	**< 0.0001**	0.112	0.291	0.339	0.336	0.190	0.769	0.367	0.250
Yield	**< 0.0001**	**0**	0.147	**0.000**	**0.017**	0.173	0.182	0.466	0.384	0.547	0.920	0.630
Berry Weight	**0.000**	0.147	**0**	0.114	0.109	0.677	0.620	0.175	**0.001**	0.837	0.387	0.114
pH	**< 0.0001**	**0.000**	0.114	**0**	**0.000**	**0.010**	0.283	0.480	0.374	0.645	0.850	0.219
Brix	0.112	**0.017**	0.109	**0.000**	**0**	**0.003**	0.603	0.237	0.604	0.123	0.898	0.833
TA	0.291	0.173	0.677	**0.010**	**0.003**	**0**	0.196	0.256	0.280	0.405	0.757	0.544
Terpene	0.339	0.182	0.620	0.283	0.603	0.196	**0**	0.267	0.870	0.226	0.190	0.412
Soil Moisture	0.336	0.466	0.175	0.480	0.237	0.256	0.267	**0**	0.180	0.744	0.903	0.347
LWP	0.190	0.384	**0.001**	0.374	0.604	0.280	0.870	0.180	**0**	0.407	0.430	0.896
Bud Survival	0.769	0.547	0.837	0.645	0.123	0.405	0.226	0.744	0.407	**0**	0.385	0.263
Mean Bud LT50	0.367	0.920	0.387	0.850	0.898	0.757	0.190	0.903	0.430	0.385	**0**	0.552
Vine size	0.250	0.630	0.114	0.219	0.833	0.544	0.412	0.347	0.896	0.263	0.552	**0**

Table A45 *p*-value correlation table for vine characteristics and winter variables for Lambert Riesling, 2010. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	January Bud LT50	Feb Bud LT50	Bud Survival	Mean Bud LT50	Vine size
Soil Moisture	**0**	0.180	0.348	0.470	0.639	0.744	0.903	0.347
LWP	0.180	**0**	0.528	0.575	0.464	0.407	0.430	0.896
Dec Bud LT50	0.348	0.528	**0**	0.436	0.081	0.473	**0.002**	0.628
January Bud LT50	0.470	0.575	0.436	**0**	**0.011**	0.433	**< 0.0001**	0.794
Feb Bud LT50	0.639	0.464	0.081	**0.011**	**0**	0.059	**< 0.0001**	0.546
Bud Survival	0.744	0.407	0.473	0.433	0.059	**0**	0.385	0.263
Mean Bud LT50	0.903	0.430	**0.002**	**< 0.0001**	**< 0.0001**	0.385	**0**	0.552
Vine size	0.347	0.896	0.628	0.794	0.546	0.263	0.552	**0**

Table A46 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Lambert Riesling, 2011. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Terpene (Monoterpene concentration) and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry weight	pH	Brix	TA	Terpene	Soil Moisture	LWP	Mean Bud LT50	Vine size
Cluster #	**0**	**< 0.0001**	0.642	**< 0.0001**	0.145	0.356	0.931	0.391	0.978	**0.025**	0.733
Yield	**< 0.0001**	**0**	0.387	**< 0.0001**	0.380	0.852	0.350	0.898	0.632	0.605	0.792
Berry weight	0.642	0.387	**0**	0.592	0.722	0.329	0.371	0.640	0.219	0.307	0.461
pH	**< 0.0001**	**< 0.0001**	0.592	**0**	**0.003**	**0.026**	0.190	0.840	0.106	0.106	0.253
Brix	0.145	0.380	0.722	**0.003**	**0**	**< 0.0001**	0.289	0.521	**0.019**	0.369	0.910
TA	0.356	0.852	0.329	**0.026**	**< 0.0001**	**0**	0.361	0.167	**0.012**	0.134	0.257
Terpene	0.931	0.350	0.371	0.190	0.289	0.361	**0**	0.715	0.583	0.527	0.881
Soil Moisture	0.391	0.898	0.640	0.840	0.521	0.167	0.715	**0**	0.273	0.470	0.490
LWP	0.978	0.632	0.219	0.106	**0.019**	**0.012**	0.583	0.273	**0**	0.398	0.323
Mean Bud LT50	**0.025**	0.605	0.307	0.106	0.369	0.134	0.527	0.470	0.398	**0**	0.566
Vine size	0.733	0.792	0.461	0.253	0.910	0.257	0.881	0.490	0.323	0.566	**0**

Table A47 *p*-value correlation table for vine characteristics and winter variables for Lambert Riesling, 2011. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	Leaf water potential	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Mean Bud LT50	Vine size
Soil Moisture	**0**	0.273	0.215	0.608	0.645	0.470	0.490
Leaf water potential	0.273	**0**	0.376	0.617	0.888	0.398	0.323
Dec Bud LT50	0.215	0.376	**0**	0.282	0.076	**0.005**	0.892
Jan Bud LT50	0.608	0.617	0.282	**0**	0.785	**0.030**	0.127
Feb Bud LT50	0.645	0.888	0.076	0.785	**0**	**< 0.0001**	0.662
Mean Bud LT50	0.470	0.398	**0.005**	**0.030**	**< 0.0001**	**0**	0.566
Vine size	0.490	0.323	0.892	0.127	0.662	0.566	**0**

Table A48 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Cave Spring Riesling, 2010. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Terpene (Monoterpene concentration) and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry Weight	pH	Brix	TA	Terpene	Soil moisture	LWP	Vine size	Bud survival	Mean Bud LT50
Cluster #	**0**	**< 0.0001**	0.621	**< 0.0001**	0.771	0.421	0.934	0.121	**0.036**	0.443	0.440	0.468
Yield	**< 0.0001**	**0**	0.996	**< 0.0001**	0.785	0.202	0.475	0.560	**0.025**	0.693	0.217	0.167
Berry Weight	0.621	0.996	**0**	**0.006**	0.982	**0.033**	0.567	0.240	0.330	**< 0.0001**	0.682	0.234
pH	**< 0.0001**	**< 0.0001**	**0.006**	**0**	0.681	0.156	0.527	**0.043**	0.058	**0.011**	0.516	0.665
Brix	0.771	0.785	0.982	0.681	**0**	**< 0.0001**	**0.030**	0.256	0.276	0.556	0.287	**0.025**
TA	0.421	0.202	**0.033**	0.156	**< 0.0001**	**0**	**0.002**	0.620	0.251	0.554	0.144	**0.027**
Terpene	0.934	0.475	0.567	0.527	**0.030**	**0.002**	**0**	0.730	0.581	0.504	0.675	0.054
Soil moisture	0.121	0.560	0.240	**0.043**	0.256	0.620	0.730	**0**	0.196	0.063	0.091	0.642
LWP	**0.036**	**0.025**	0.330	0.058	0.276	0.251	0.581	0.196	**0**	0.105	0.456	0.090
Vine size	0.443	0.693	**< 0.0001**	**0.011**	0.556	0.554	0.504	0.063	0.105	**0**	0.551	0.527
Bud survival	0.440	0.217	0.682	0.516	0.287	0.144	0.675	0.091	0.456	0.551	**0**	0.738
Mean Bud LT50	0.468	0.167	0.234	0.665	**0.025**	**0.027**	0.054	0.642	0.090	0.527	0.738	**0**

Table A49 *p*-value correlation table for vine characteristics and winter variables for Cave Spring Riesling, 2010. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Vine size	Bud survival	Mean Bud LT50
Soil moisture	**0**	0.196	0.945	0.247	0.745	0.063	0.091	0.642
LWP	0.196	**0**	0.154	0.094	0.638	0.105	0.456	0.090
Dec Bud LT50	0.945	0.154	**0**	0.069	**0.000**	0.991	0.921	**< 0.0001**
Jan Bud LT50	0.247	0.094	0.069	**0**	0.486	0.503	0.666	**0.001**
Feb Bud LT50	0.745	0.638	**0.000**	0.486	**0**	0.405	0.714	**0.000**
Vine size	0.063	0.105	0.991	0.503	0.405	**0**	0.551	0.527
Bud survival	0.091	0.456	0.921	0.666	0.714	0.551	**0**	0.738
Mean Bud LT50	0.642	0.090	**< 0.0001**	**0.001**	**0.000**	0.527	0.738	**0**

Table A50 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Cave Spring Riesling, 2011. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Terpene (Monoterpene concentration) and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry weight	Brix	pH	TA	Terpene	Soil Moisture	LWP	Mean Bud LT50	Bud Survival	Vine size
Cluster #	**0**	**< 0.0001**	0.072	0.162	0.688	0.886	0.323	0.764	0.052	0.080	0.932	**0.017**
Yield	**< 0.0001**	**0**	0.076	**0.014**	0.391	0.734	0.465	0.818	0.262	0.101	0.921	**0.002**
Berry weight	0.072	0.076	**0**	0.853	**0.021**	**0.008**	0.689	**0.044**	**0.020**	**0.005**	0.569	0.352
Brix	0.162	**0.014**	0.853	**0**	0.245	**< 0.0001**	0.099	0.569	0.902	0.360	0.269	0.760
pH	0.688	0.391	**0.021**	0.245	**0**	0.294	**0.015**	**0.012**	0.105	0.493	0.836	0.535
TA	0.886	0.734	**0.008**	**< 0.0001**	0.294	**0**	0.333	**0.041**	0.209	**0.014**	0.735	0.310
Terpene	0.323	0.465	0.689	0.099	**0.015**	0.333	**0**	0.141	0.710	0.447	0.592	0.481
Soil Moisture	0.764	0.818	**0.044**	0.569	**0.012**	**0.041**	0.141	**0**	0.439	0.197	0.343	0.409
LWP	0.052	0.262	**0.020**	0.902	0.105	0.209	0.710	0.439	**0**	**0.042**	0.118	0.656
Mean Bud LT50	0.080	0.101	**0.005**	0.360	0.493	**0.014**	0.447	0.197	**0.042**	**0**	0.773	0.553
Bud Survival	0.932	0.921	0.569	0.269	0.836	0.735	0.592	0.343	0.118	0.773	**0**	0.261
Vine size	**0.017**	**0.002**	0.352	0.760	0.535	0.310	0.481	0.409	0.656	0.553	0.261	**0**

Table A51 *p*-value correlation table for vine characteristics and winter variables for Cave Spring Riesling, 2011. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Mean Bud LT50	Bud Survival	Vine size
Soil Moisture (%)	**0**	0.439	0.075	0.560	0.251	0.197	0.343	0.409
Leaf water potential (bar)	0.439	**0**	**0.020**	0.655	0.355	**0.042**	0.118	0.656
Dec Bud LT50 (Celsius)	0.075	**0.020**	**0**	0.157	0.161	**0.001**	0.524	0.384
Jan Bud LT50 (Celsius)	0.560	0.655	0.157	**0**	**0.031**	**0.002**	0.965	0.768
Feb Bud LT50 (Celsius)	0.251	0.355	0.161	**0.031**	**0**	**< 0.0001**	0.373	0.753
Mean Bud LT50 (Celsius)	0.197	**0.042**	**0.001**	**0.002**	**< 0.0001**	**0**	0.773	0.553
Bud Survival (%)	0.343	0.118	0.524	0.965	0.373	0.773	**0**	0.261
Vine size (g)	0.409	0.656	0.384	0.768	0.753	0.553	0.261	**0**

Table A52 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Lowrey Riesling, 2010. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Terpene (Monoterpene concentration) and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry weight	Brix	pH	TA	Terpene	Soil Moisture	LWP	Mean Bud LT50	Bud Survival	Vine size
Cluster #	**0**	**< 0.0001**	0.858	**0.035**	0.108	0.765	0.657	0.898	0.528	0.263	0.233	**< 0.0001**
Yield	**< 0.0001**	**0**	**< 0.0001**	0.222	0.136	**0.038**	0.076	0.249	0.226	0.354	0.230	**< 0.0001**
Berry weight	0.858	**< 0.0001**	**0**	**< 0.0001**	0.259	**0.002**	0.387	0.959	0.103	0.861	0.538	**< 0.0001**
Brix	**0.035**	0.222	**< 0.0001**	**0**	0.112	**< 0.0001**	**0.046**	0.956	0.052	0.199	0.370	0.216
pH	0.108	0.136	0.259	0.112	**0**	0.156	0.108	0.105	0.124	0.054	0.536	0.614
TA	0.765	**0.038**	**0.002**	**< 0.0001**	0.156	**0**	0.085	0.139	0.061	0.892	0.647	0.393
Terpene	0.657	0.076	0.387	**0.046**	0.108	0.085	**0**	0.475	0.854	0.732	0.802	0.108
Soil Moisture	0.898	0.249	0.959	0.956	0.105	0.139	0.475	**0**	0.335	0.464	0.586	0.619
LWP	0.528	0.226	0.103	0.052	0.124	0.061	0.854	0.335	**0**	0.842	0.608	0.351
Mean Bud LT50	0.263	0.354	0.861	0.199	0.054	0.892	0.732	0.464	0.842	**0**	0.572	0.896
Bud Survival	0.233	0.230	0.538	0.370	0.536	0.647	0.802	0.586	0.608	0.572	**0**	0.375
Vine size	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.216	0.614	0.393	0.108	0.619	0.351	0.896	0.375	**0**

Table A53 *p*-value correlation table for vine characteristics and winter variables for Lowrey Riesling, 2010. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Bud Survival	Vine size	Mean Bud LT50	December Bud LT50	January Bud LT50	February Bud LT50
Soil Moisture	**0**	0.205	0.206	0.288	0.264	0.589	0.426	0.236
Leaf Water Potential	0.205	**0**	0.562	0.288	0.275	0.173	0.994	0.113
Bud Survival	0.206	0.562	**0**	0.547	0.377	0.936	0.430	0.613
Vine size	0.288	0.288	0.547	**0**	0.270	0.641	0.508	0.615
Mean Bud LT50	0.264	0.275	0.377	0.270	**0**	**0.004**	**< 0.0001**	**0.023**
December Bud LT50	0.589	0.173	0.936	0.641	**0.004**	**0**	0.804	0.349
January Bud LT50	0.426	0.994	0.430	0.508	**< 0.0001**	0.804	**0**	0.850
February Bud LT50	0.236	0.113	0.613	0.615	**0.023**	0.349	0.850	**0**

Table A54 *p*-value correlation table for berry composition, vine characteristics, bud survival, and mean bud LT50 for Lowrey Riesling, 2011. Bolded values are significant. Short forms are used for variables including Cluster # (Cluster number), TA (titratable acidity), Terpene (Monoterpene concentration) and LWP (Leaf water potential). Units are not included.

Variables	Cluster #	Yield	Berry weight	Brix	pH	TA	Terpene	Soil Moisture	LWP	Mean Bud LT50	Bud Survival	Vine size
Cluster #	**0**	**< 0.0001**	0.858	**0.035**	0.108	0.765	0.657	0.898	0.528	0.263	0.233	**< 0.0001**
Yield	**< 0.0001**	**0**	**< 0.0001**	0.222	0.136	**0.038**	0.076	0.249	0.226	0.354	0.230	**< 0.0001**
Berry weight	0.858	**< 0.0001**	**0**	**< 0.0001**	0.259	**0.002**	0.387	0.959	0.103	0.861	0.538	**< 0.0001**
Brix	**0.035**	0.222	**< 0.0001**	**0**	0.112	**< 0.0001**	**0.046**	0.956	0.052	0.199	0.370	0.216
pH	0.108	0.136	0.259	0.112	**0**	0.156	0.108	0.105	0.124	0.054	0.536	0.614
TA	0.765	**0.038**	**0.002**	**< 0.0001**	0.156	**0**	0.085	0.139	0.061	0.892	0.647	0.393
Terpene	0.657	0.076	0.387	**0.046**	0.108	0.085	**0**	0.475	0.854	0.732	0.802	0.108
Soil Moisture	0.898	0.249	0.959	0.956	0.105	0.139	0.475	**0**	0.335	0.464	0.586	0.619
LWP	0.528	0.226	0.103	0.052	0.124	0.061	0.854	0.335	**0**	0.842	0.608	0.351
Mean Bud LT50	0.263	0.354	0.861	0.199	0.054	0.892	0.732	0.464	0.842	**0**	0.572	0.896
Bud Survival	0.233	0.230	0.538	0.370	0.536	0.647	0.802	0.586	0.608	0.572	**0**	0.375
Vine size	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.216	0.614	0.393	0.108	0.619	0.351	0.896	0.375	**0**

Table A55 *p*-value correlation table for vine characteristics and winter variables for Lowrey Riesling, 2011. Bolded values are significant. Short forms are used for variables including LWP (Leaf water potential). Units are not included.

Variables	Soil Moisture	LWP	Dec Bud LT50	Jan Bud LT50	Feb Bud LT50	Mean Bud LT50	Bud Survival	Vine size
Soil Moisture	**0**	0.379	0.311	**0.042**	0.294	0.467	0.259	0.653
Leaf water potential	0.379	**0**	0.408	0.081	0.679	0.849	0.647	0.343
Dec Bud LT50	0.311	0.408	**0**	0.620	0.252	**0.008**	0.620	0.733
Jan Bud LT50	**0.042**	0.081	0.620	**0**	0.676	**0.018**	0.315	0.947
Feb Bud LT50	0.294	0.679	0.252	0.676	**0**	**< 0.0001**	0.180	0.914
Mean Bud LT50	0.467	0.849	**0.008**	**0.018**	**< 0.0001**	**0**	0.563	0.909
Bud Survival	0.259	0.647	0.620	0.315	0.180	0.563	**0**	0.339
Vine size	0.653	0.343	0.733	0.947	0.914	0.909	0.339	**0**

II) Figures

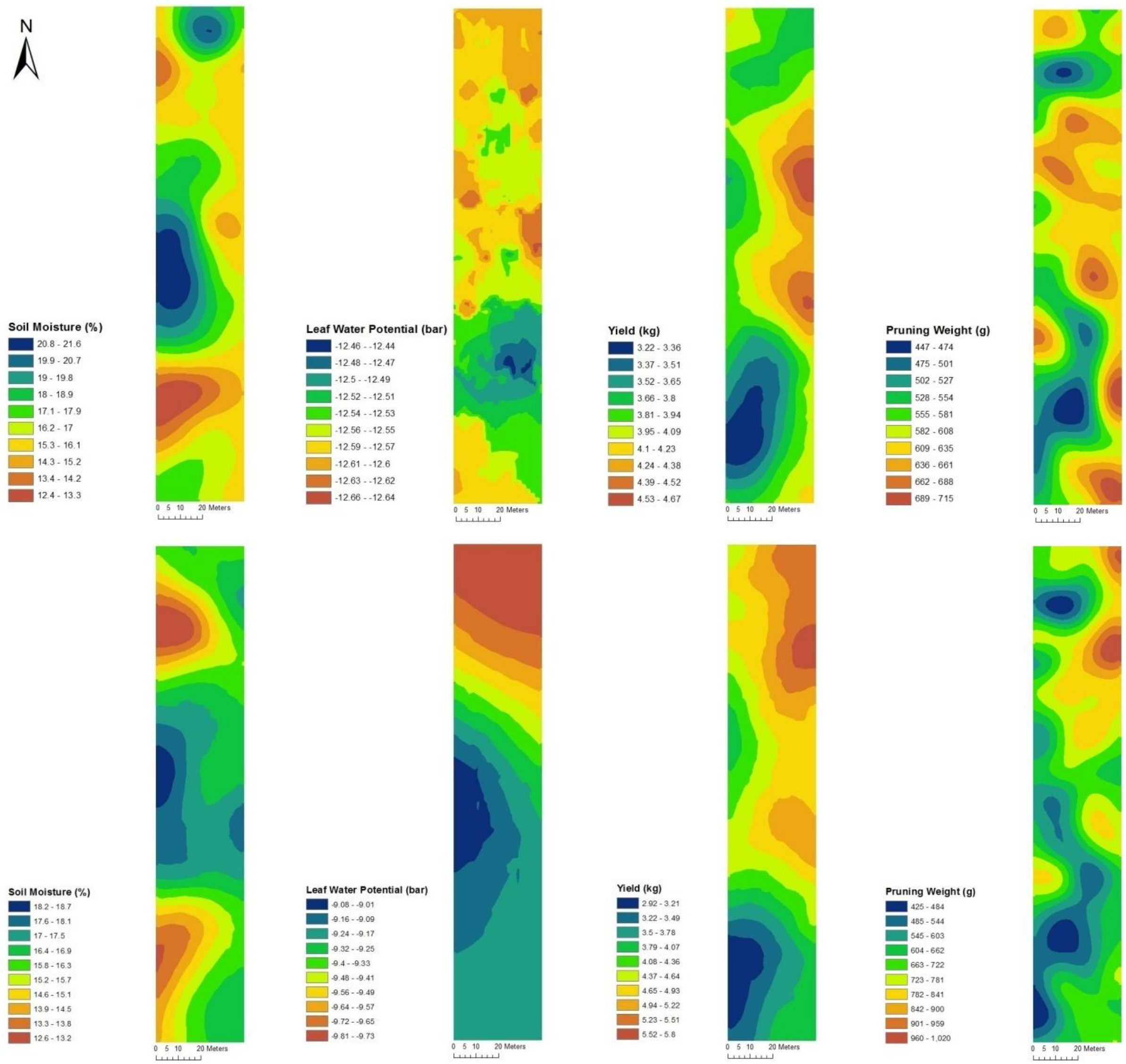


Figure A1 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Buis Cabernet franc block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and vine size. Bottom row: 2011 soil moisture, leaf ψ, yield, and vine size. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 5.0833 (clustered), z-score = -1.9184 (dispersed), and z-score = 1.688 (clustered), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 5.7167 (clustered), z-score = 0.9589 (random), and z-score = 3.5343 (clustered), respectively.

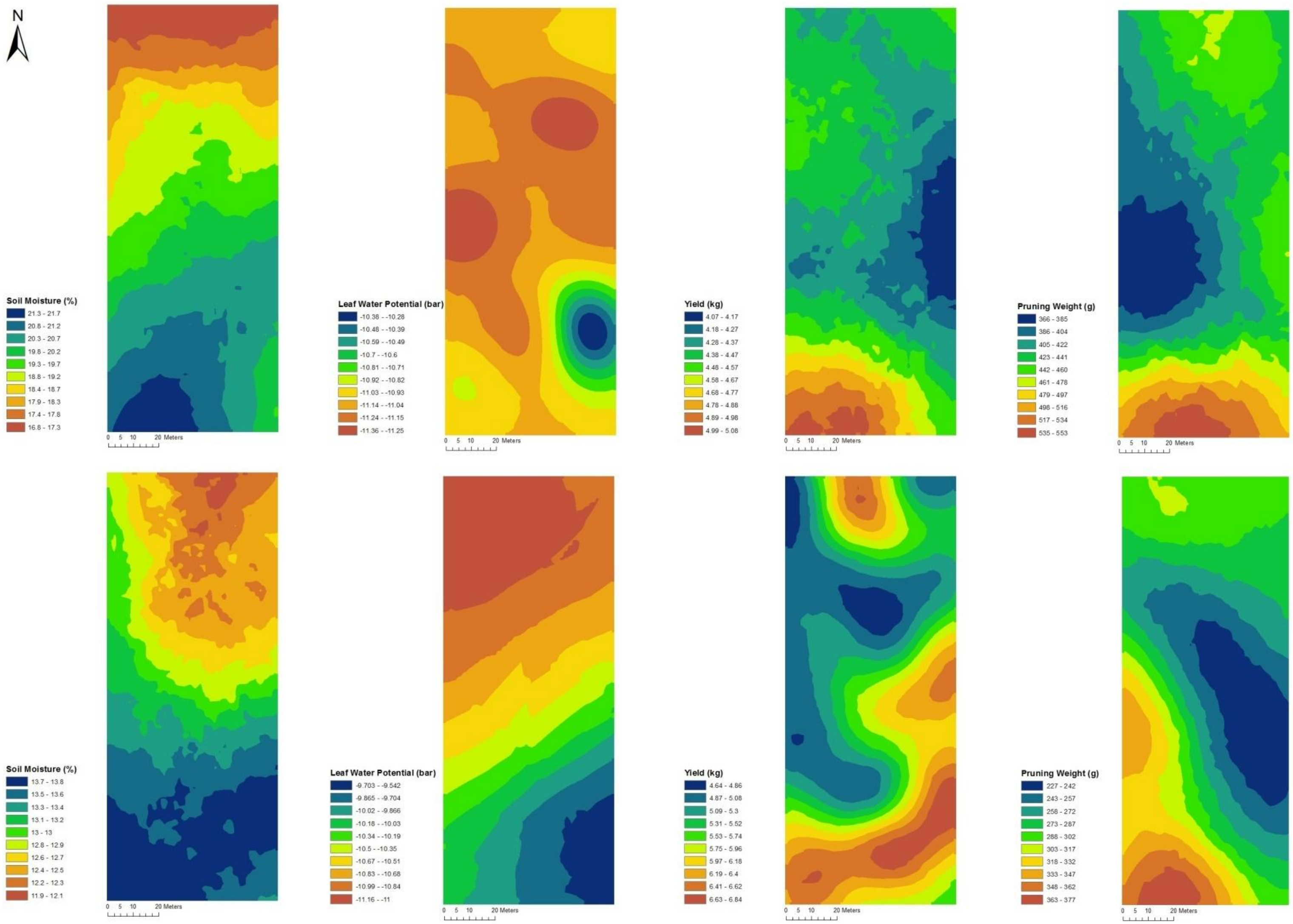


Figure A2 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the George Cabernet franc block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 2.9434 (clustered), z-score = 1.9882 (clustered), and z-score =0.0659 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 0.9114 (random), z-score = 3.2365 (clustered), and z-score = 1.5283 (random), respectively.

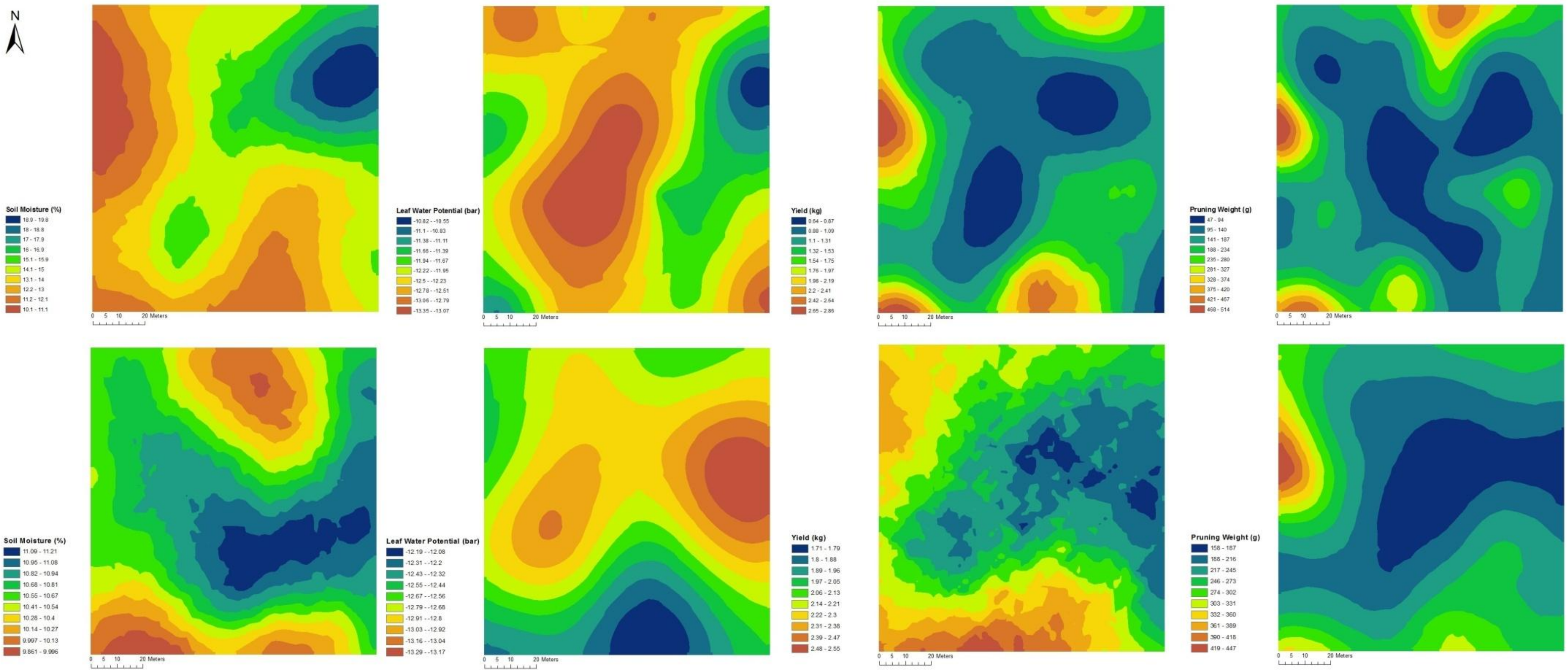


Figure A3 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Kocsis Cabernet franc block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and vine size. Bottom row: 2011 soil moisture, leaf ψ, yield, and vine size. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 4.2432 (clustered), z-score = 0.2094 (random), and z-score = 2.2269 (clustered), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 0.8474 (random), z-score = 0.3341 (random), and z-score = 1.3816 (random), respectively.

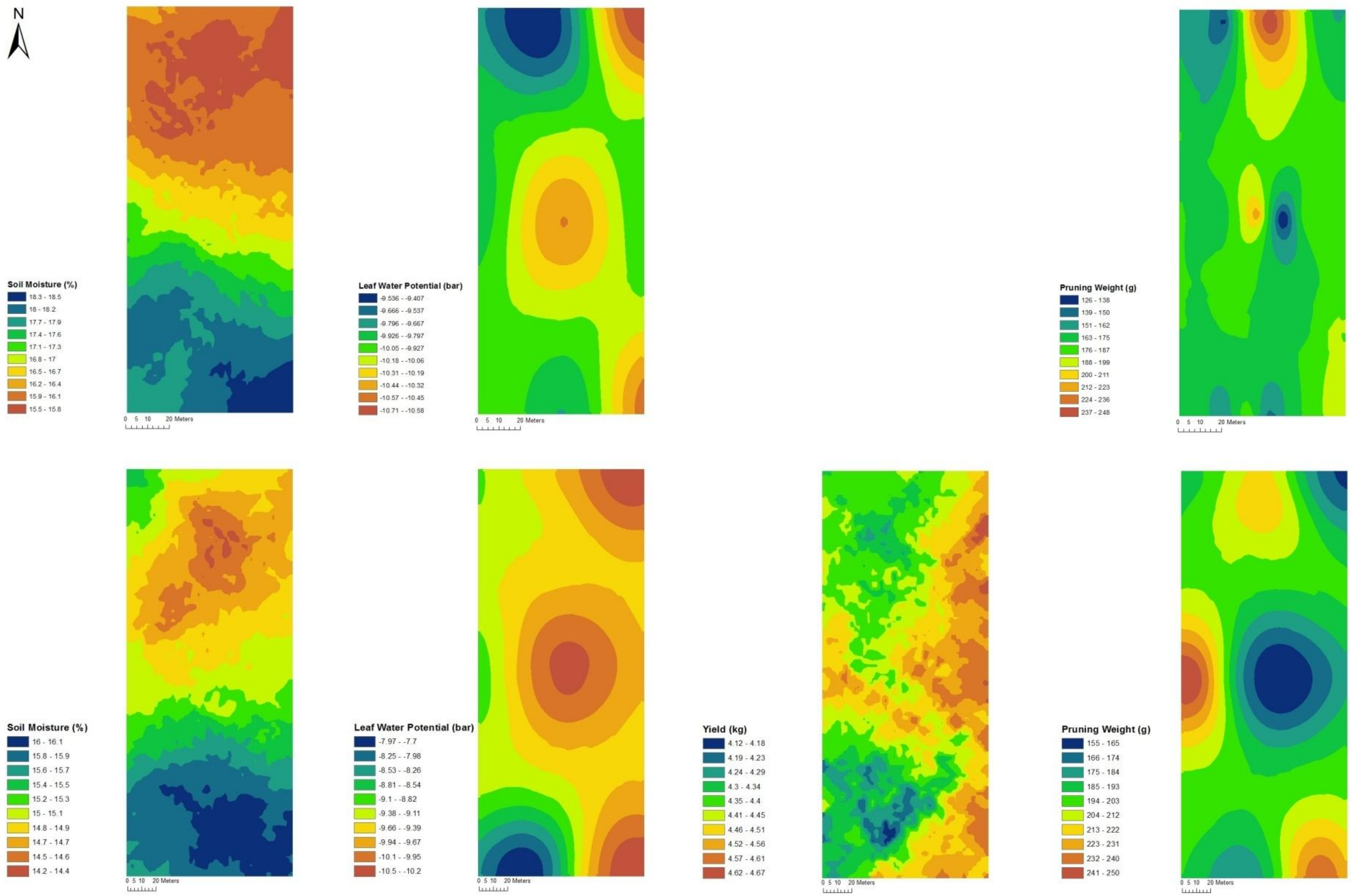


Figure A4 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Lambert Cabernet franc block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture and leaf ψ are: z-score = 3.0137 (clustered) and z-score = 1.5747 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 0.7463 (random), z-score = 2.5129 (clustered), and z-score = -0.6691 (random), respectively.

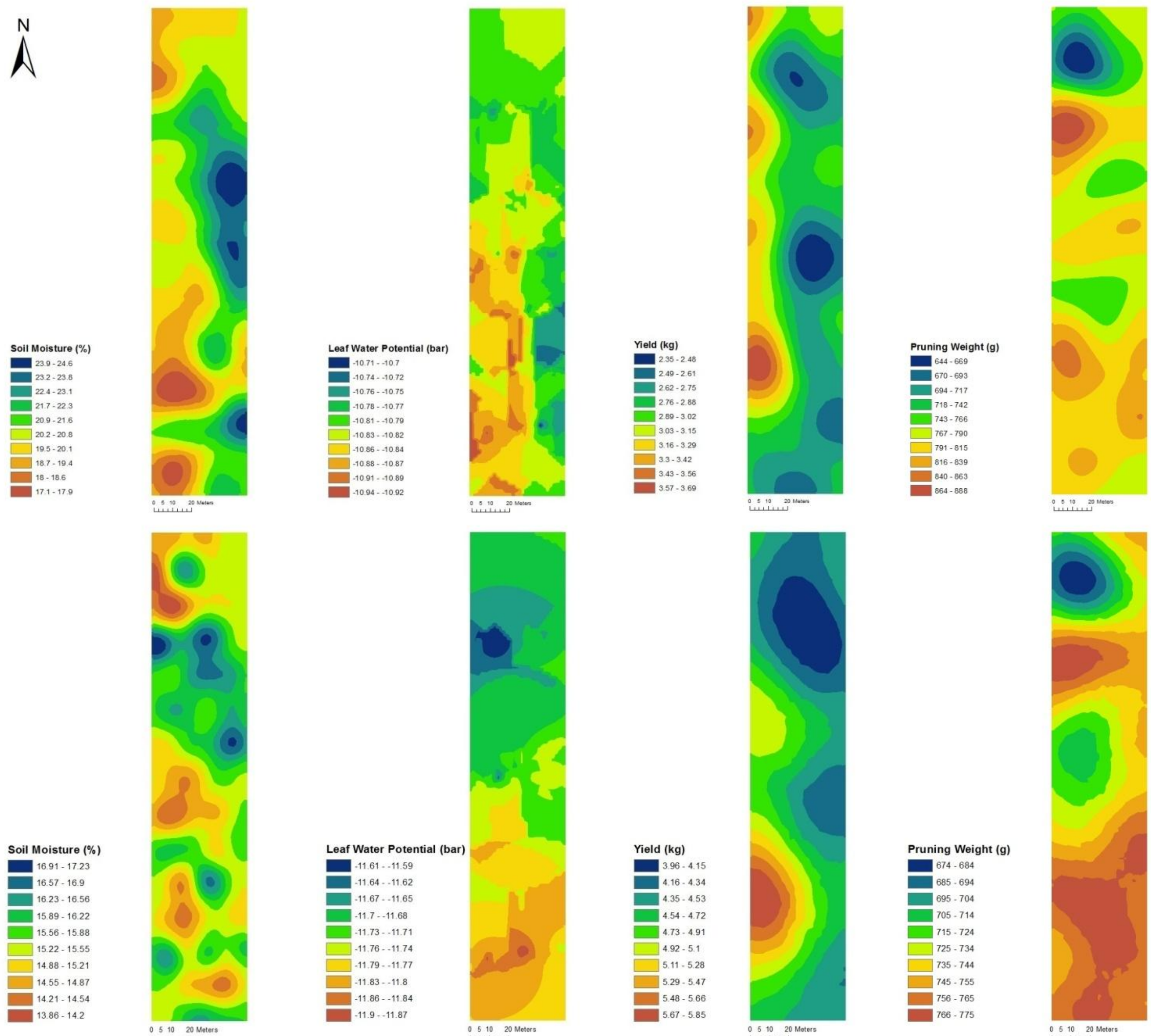


Figure A5 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Cave Spring Cabernet franc block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 3.3145 (clustered), z-score = -0.3773 (random), and z-score = 0.1508 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 2.5846 (clustered), z-score = 7.8715 (clustered), and z-score = 1.6823 (clustered), respectively.

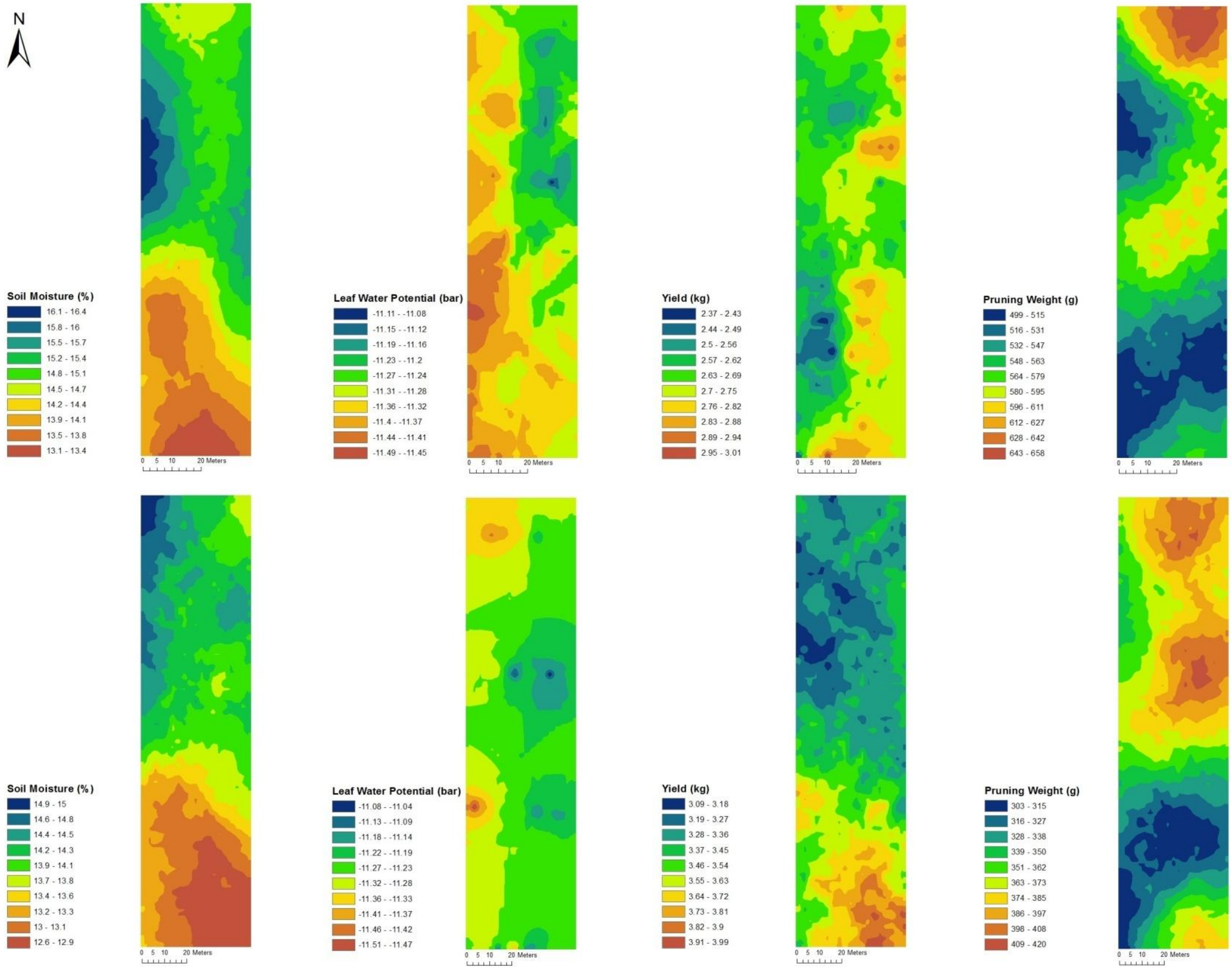


Figure A6 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Lowrey Cabernet franc block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 1.6154 (random), z-score = -0.0988 (random), and z-score = -1.3836 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 1.0417 (random), z-score = -1.7254 (dispersed), and z-score = -0.9293 (random), respectively.

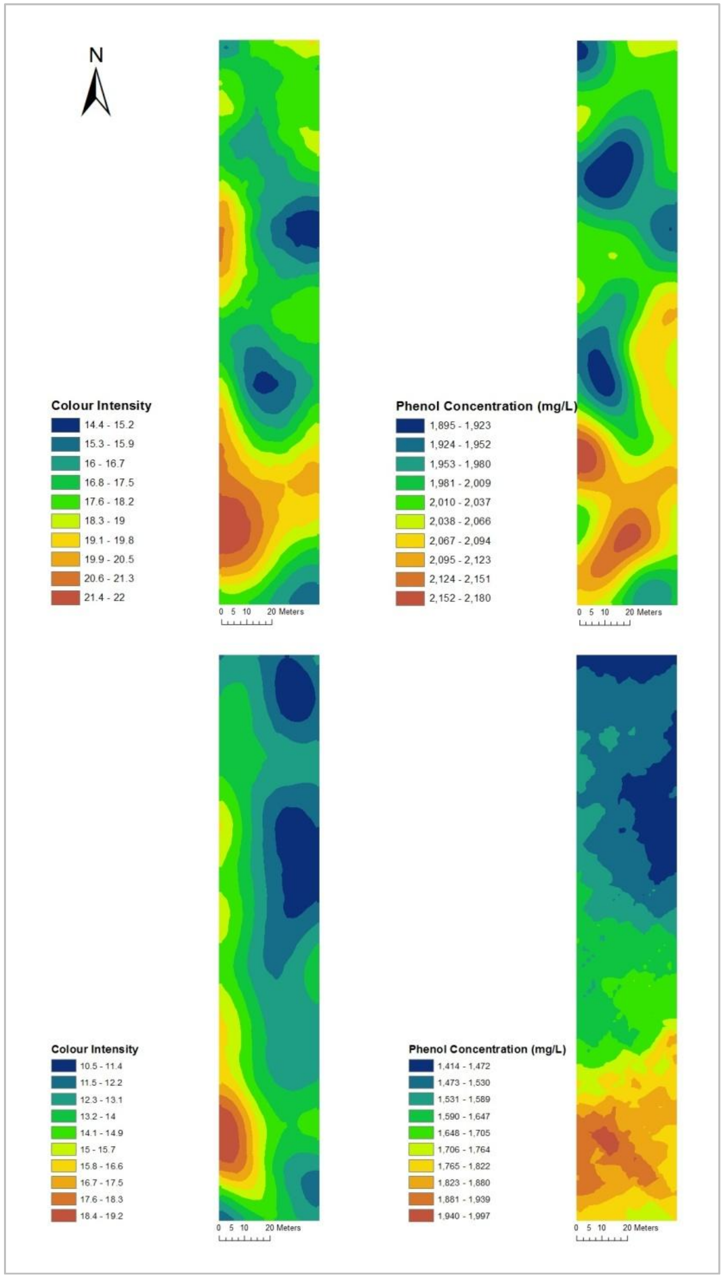


Figure A7 Maps of colour intensity and phenol concentration for the Buis Cabernet franc block in 2010 and 2011. Top: 2010 colour intensity and phenol concentration. Bottom: 2011 colour intensity and phenol concentration.

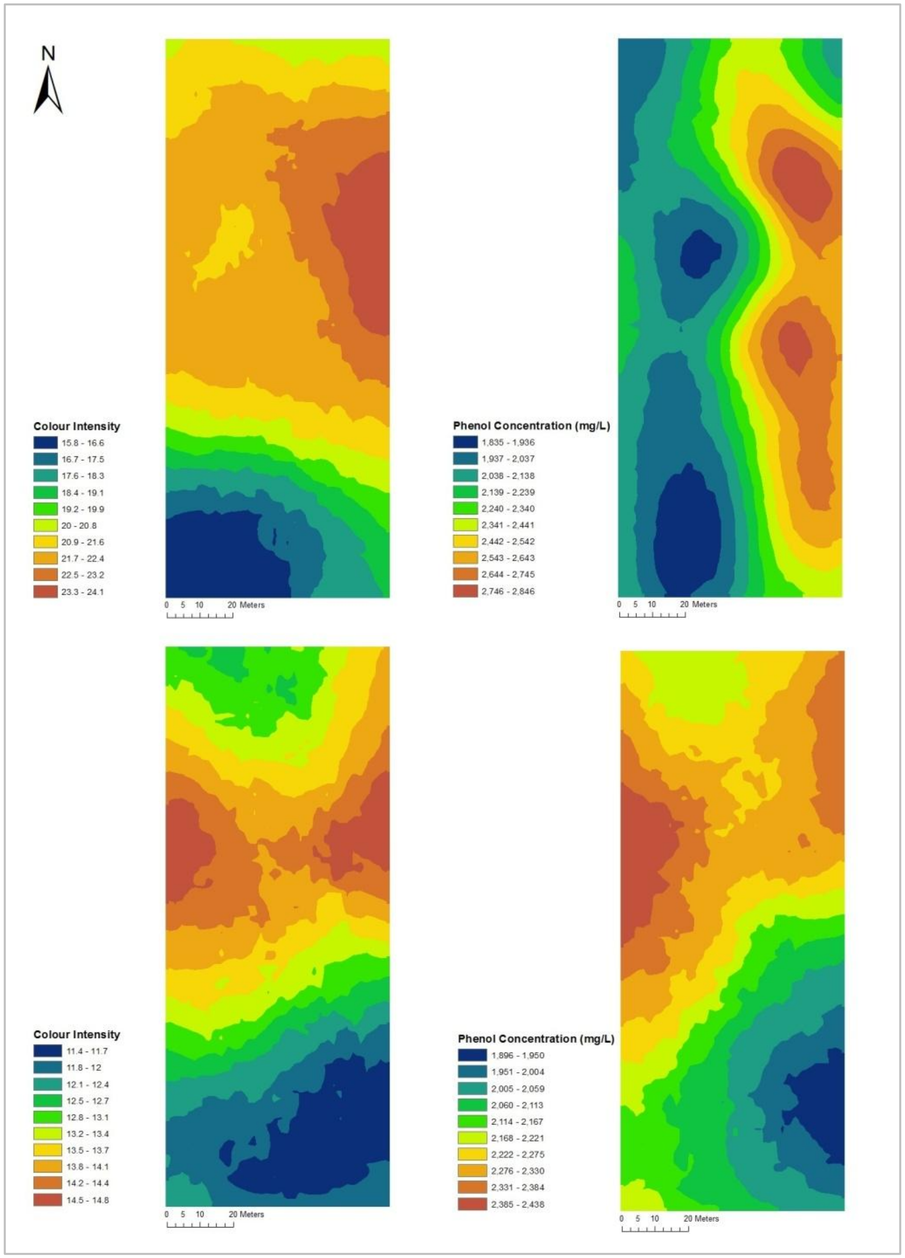


Figure A8 Maps of colour intensity and phenol concentration for the George Cabernet franc block in 2010 and 2011. Top: 2010 colour intensity and phenol concentration. Bottom: 2011 colour intensity and phenol concentration.

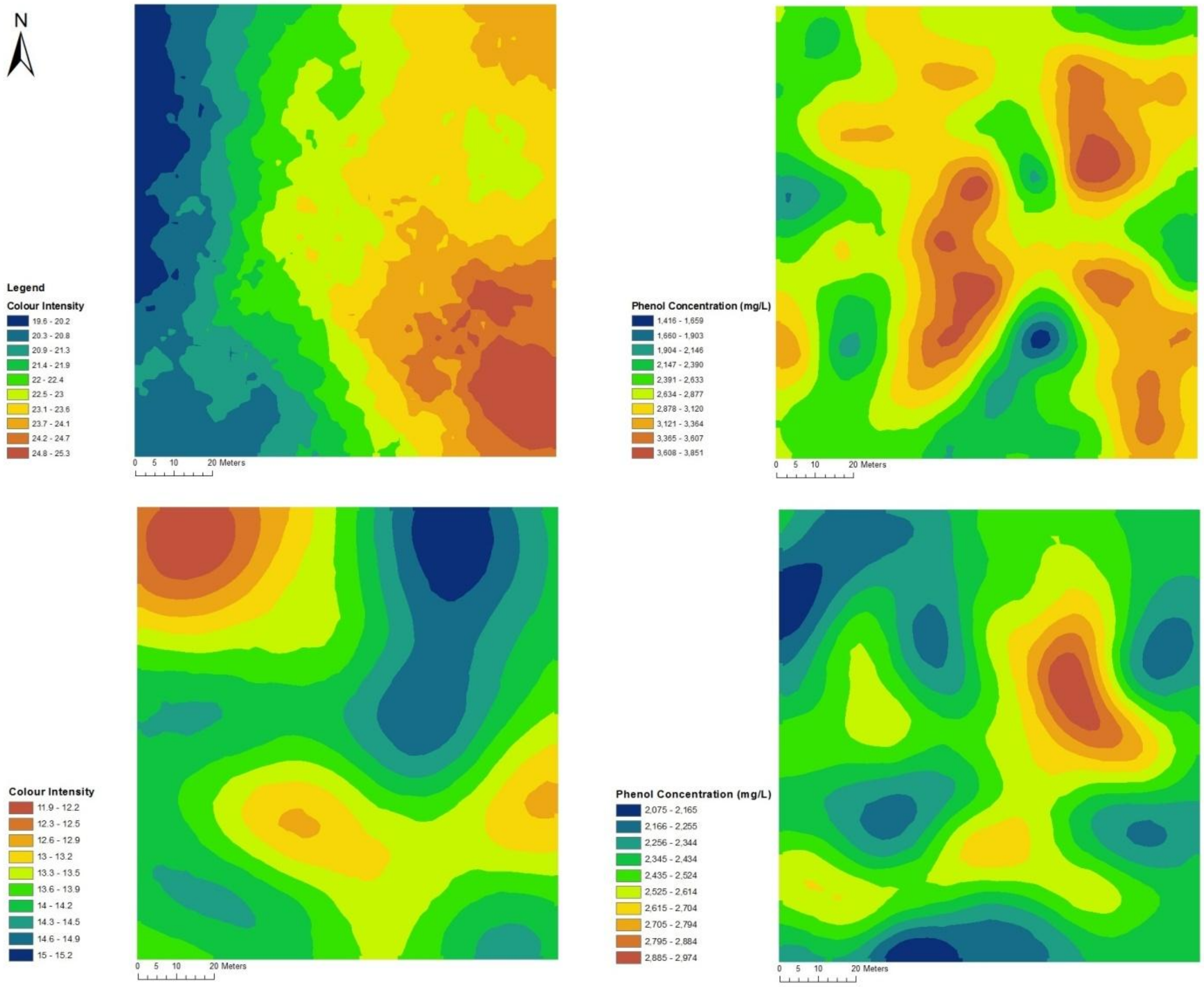


Figure A9 Maps of colour intensity and phenol concentration for the Kocsis Cabernet franc block in 2010 and 2011. Top: 2010 colour intensity and phenol concentration. Bottom: 2011 colour intensity and phenol concentration.

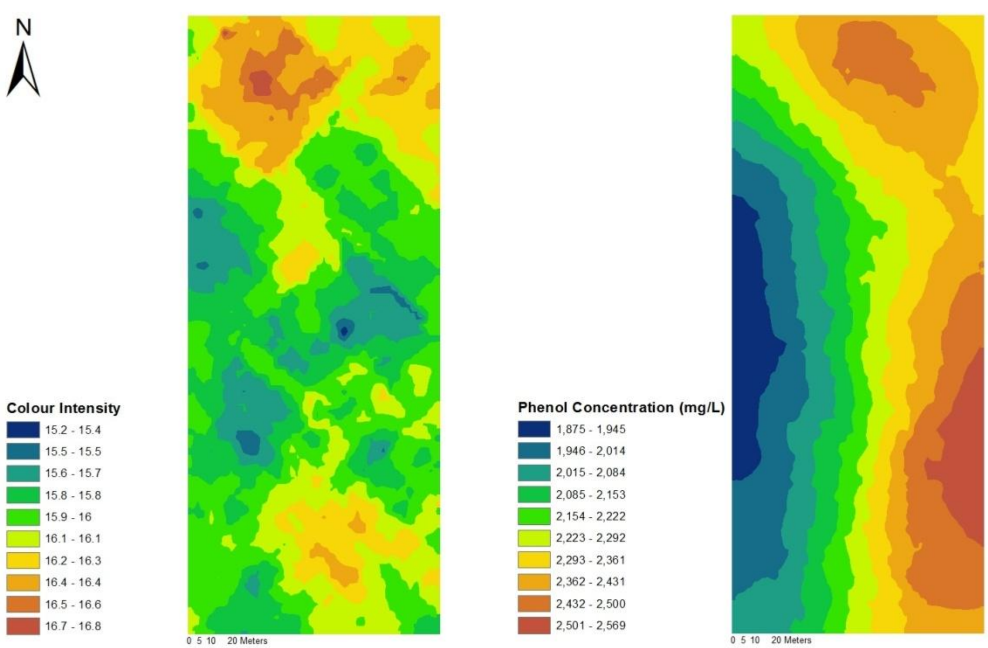


Figure A10 Maps of colour intensity and phenol concentration for the Lambert Cabernet franc block in 2011. Left: colour intensity and Right: phenol concentration.

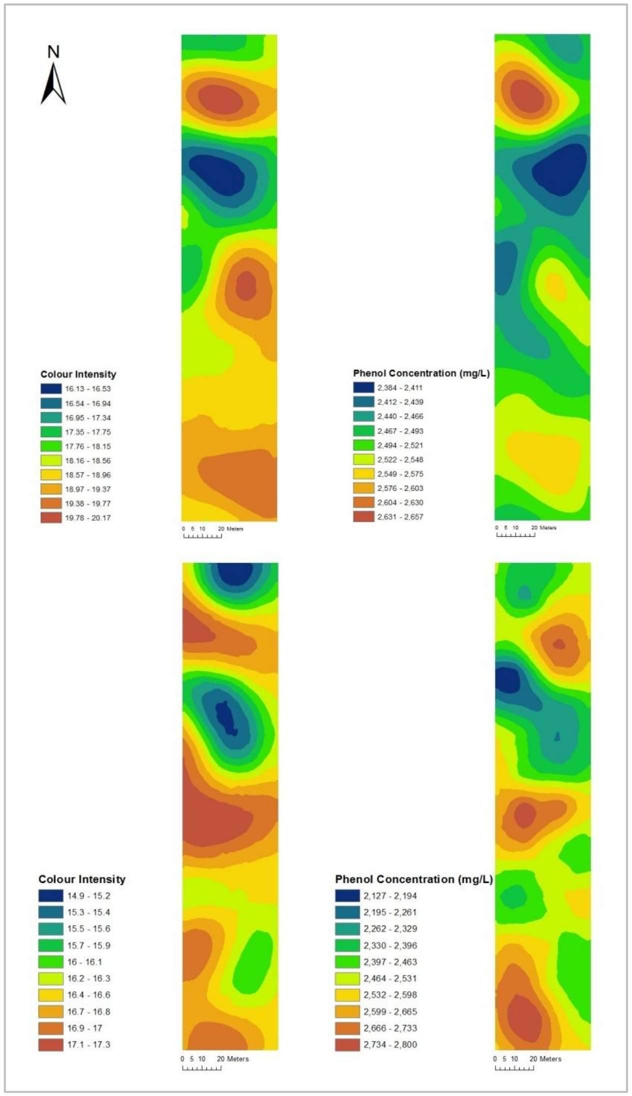


Figure A11. Maps of colour intensity and phenol concentration for the Cave Spring Cabernet franc block in 2010 and 2011. Top: 2010 colour intensity and phenol concentration. Bottom: 2011 colour intensity and phenol concentration.

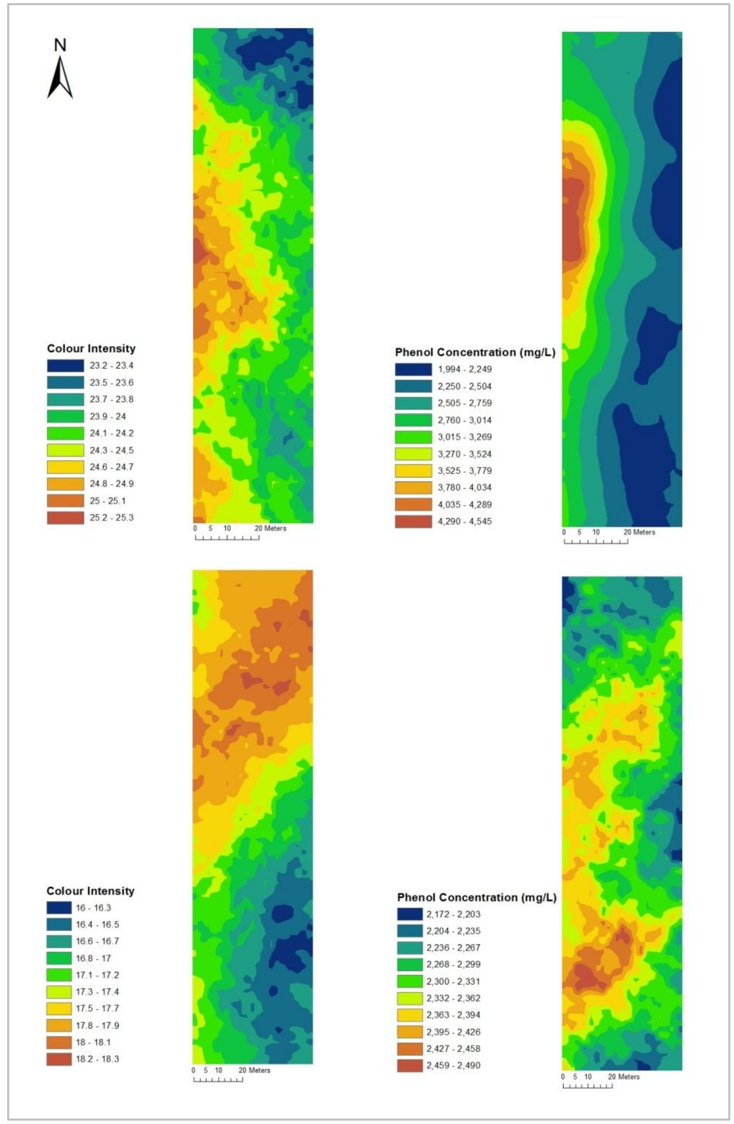


Figure A12. Maps of colour intensity and phenol concentration for the George Cabernet franc block in 2010 and 2011. Top: 2010 colour intensity and phenol concentration. Bottom: 2011 colour intensity and phenol concentration.

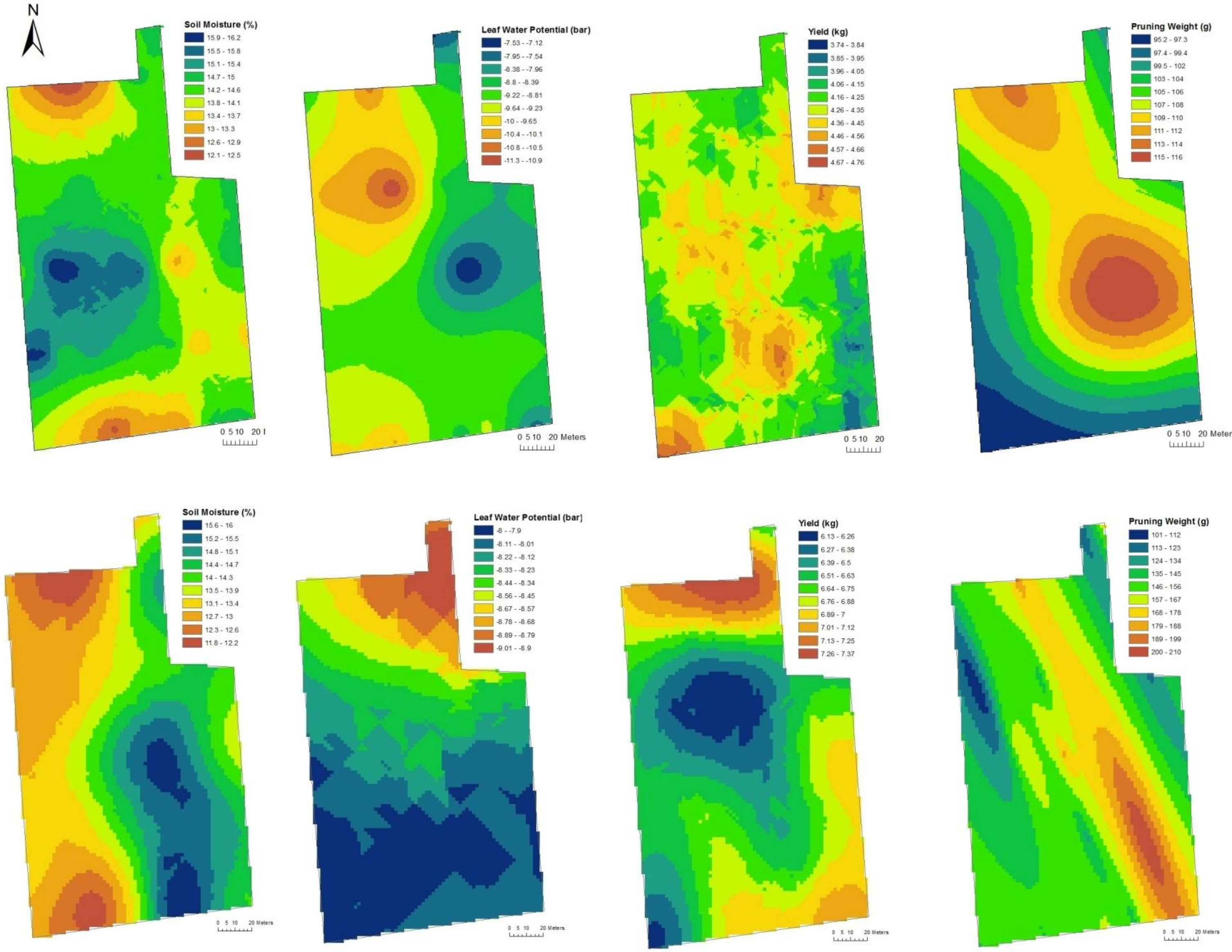


Figure A13 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Buis Riesling block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 2.8219 (clustered), z-score = -2.3459 (dispersed), and z-score = -0.1877 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 4.1285 (clustered), z-score = 0.5315 (random), and z-score = 1.0981 (random), respectively.

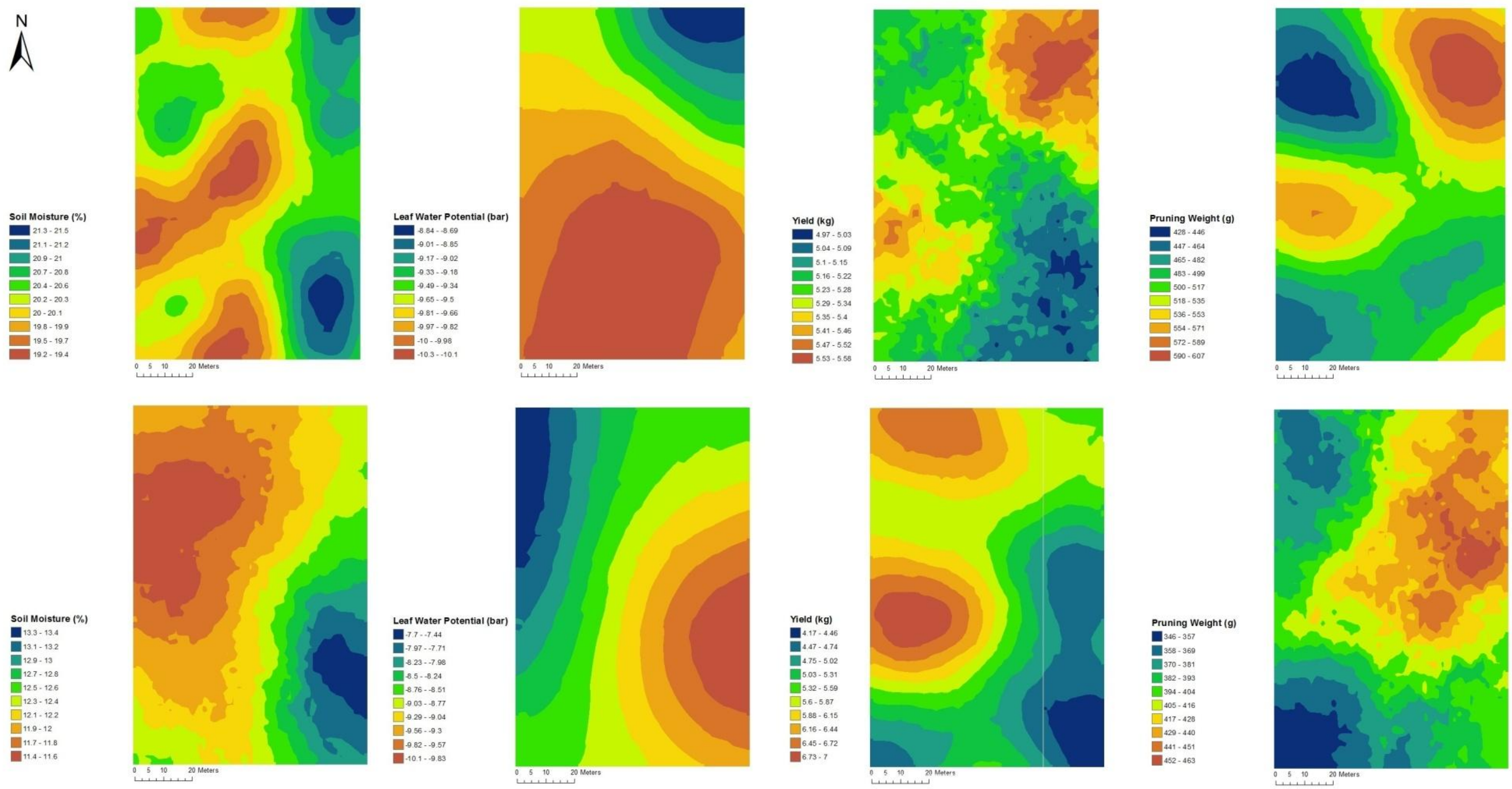


Figure A14 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the George Riesling block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 3.6332 (clustered), z-score = 1.2104 (random), and z-score = -0.3507 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 0.7377 (random), z-score = 1.8031 (clustered), and z-score = 2.1613 (clustered), respectively.

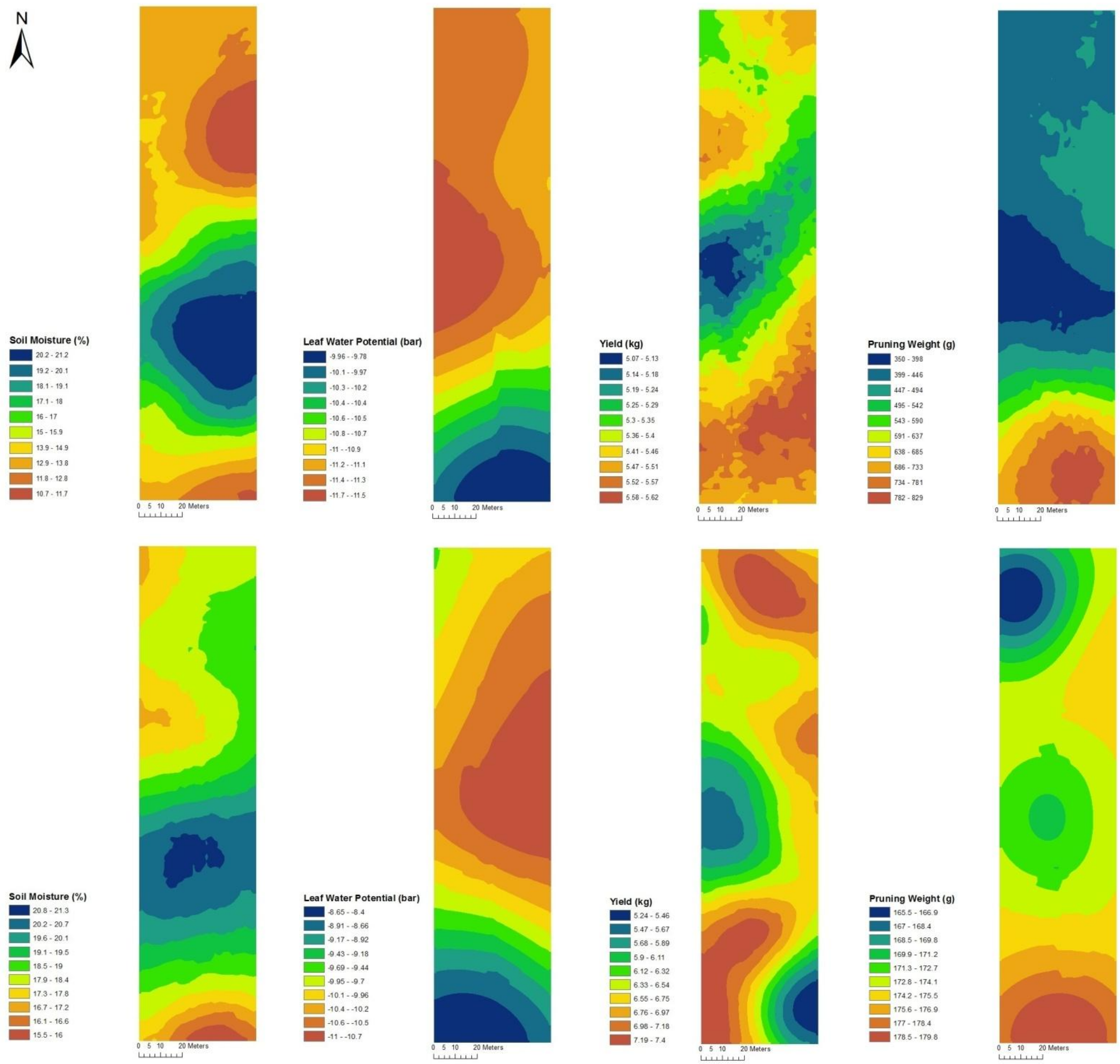


Figure A15 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Hughes Riesling block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 4.6690 (clustered), z-score = 4.6533 (clustered), and z-score = -1.0163 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 0.8497 (random), z-score = 4.2595 (clustered), and z-score = 1.2841 (random), respectively.

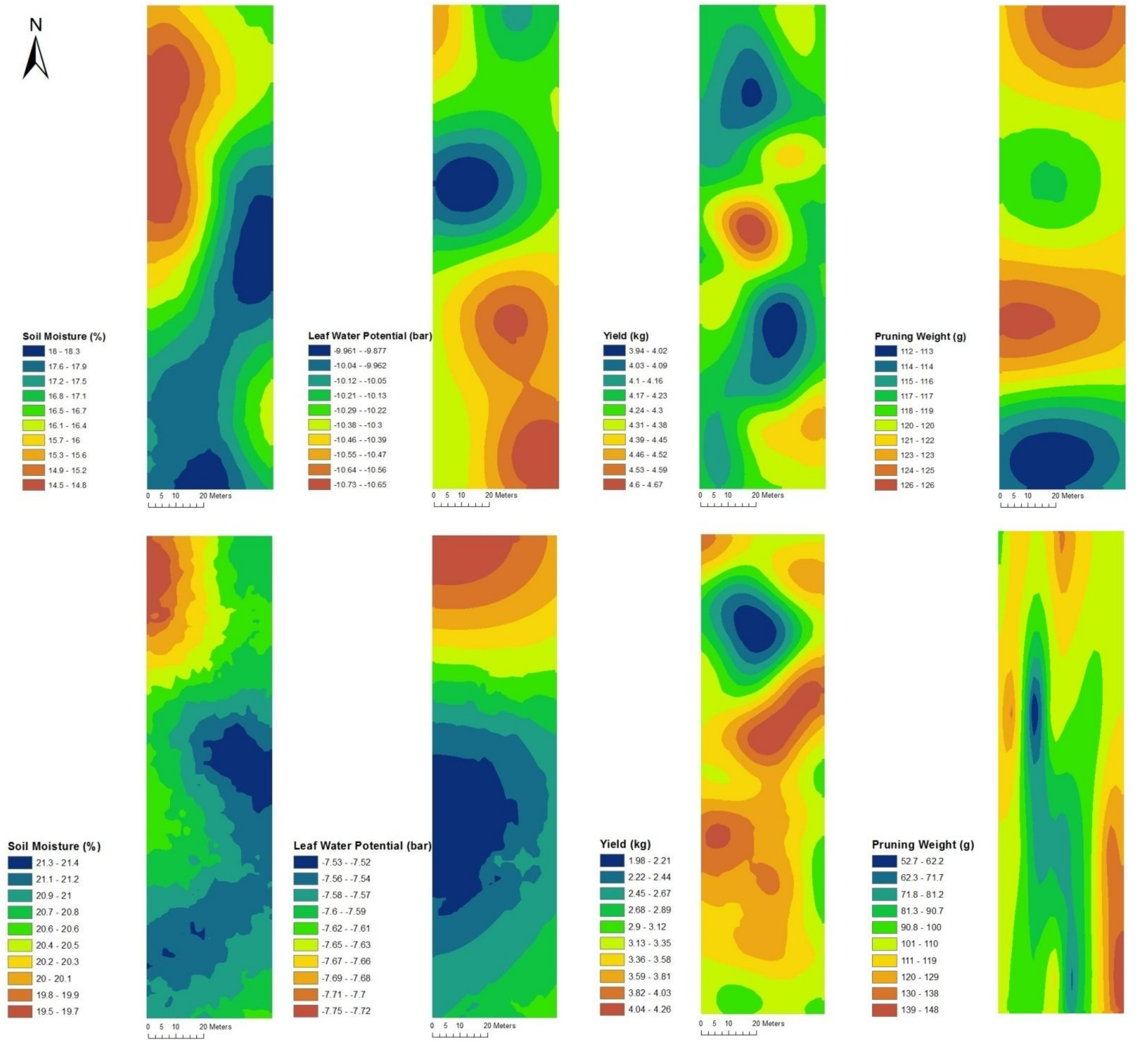


Figure A16 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Lambert Riesling block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and vine size. Bottom row: 2011 soil moisture, leaf ψ, yield, and vine size. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 3.5807 (clustered), z-score = 1.4994 (random), and z-score = 0.6064 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 1.1155 (random), z-score =-1.1223 (random), and z-score = 1.3798 (random), respectively.

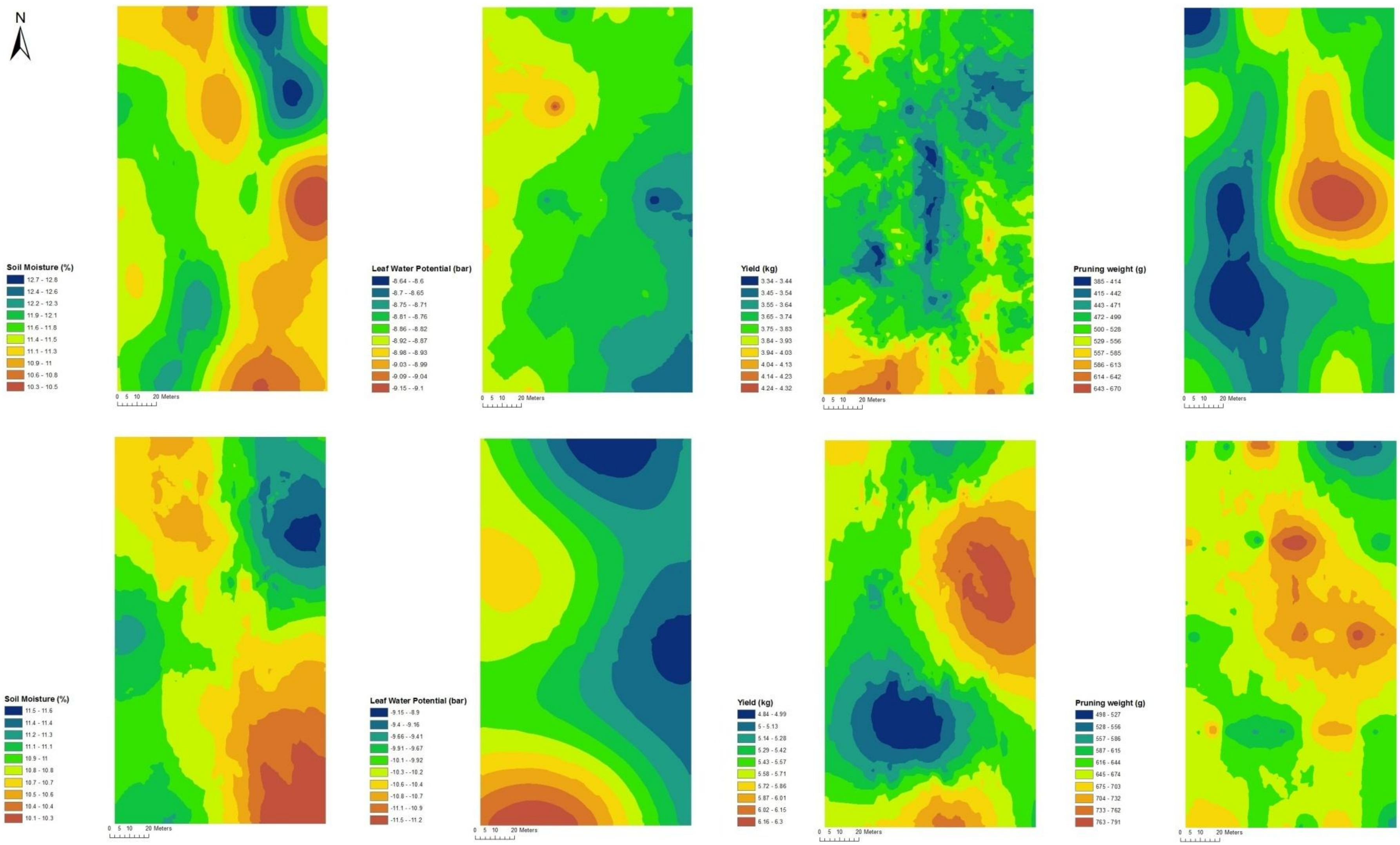


Figure A17 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Cave Spring Riesling block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 1.7576 (clustered), z-score = -1.5457 (random), and z-score = 0.7432 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 1.1309 (random), z-score = 0.7948 (random), and z-score = -0.2777 (random), respectively.

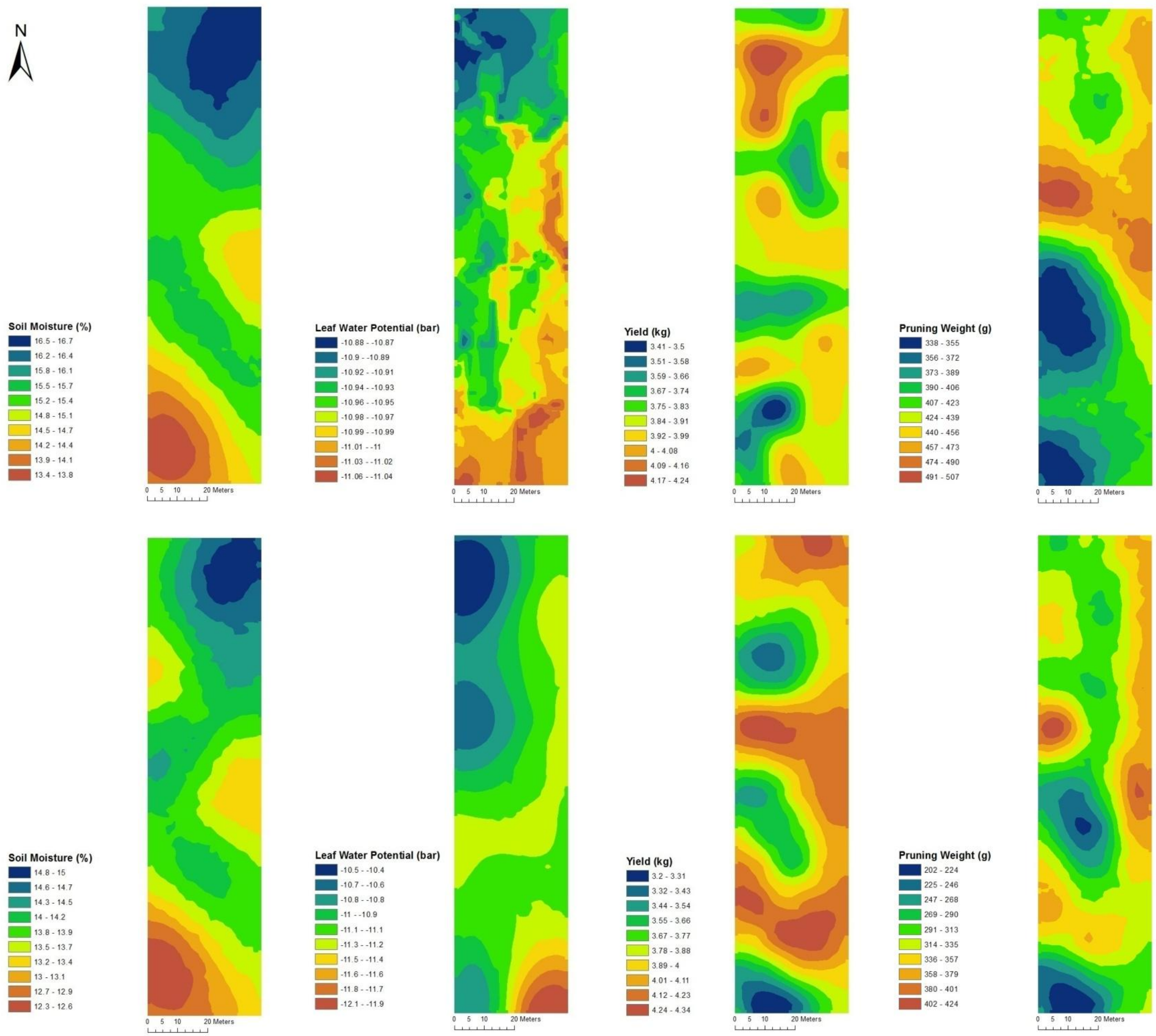


Figure A18 Maps of soil moisture, leaf ψ, yield, and pruning weight (vine size) for the Lowrey Riesling block for both 2010 and 2011. Top row: 2010 soil moisture, leaf ψ, yield, and pruning weight. Bottom row: 2011 soil moisture, leaf ψ, yield, and pruning weight. Morans I results for 2010 soil moisture, leaf ψ, and yield are: z-score = 3.1555 (clustered), z-score = -0.9960 (random), and z-score = 0.8420 (random), respectively; Morans I results for 2011 soil moisture, leaf ψ, and yield are: z-score = 0.1320 (random), z-score = 1.3239 (random), and z-score = 1.1966 (random), respectively.

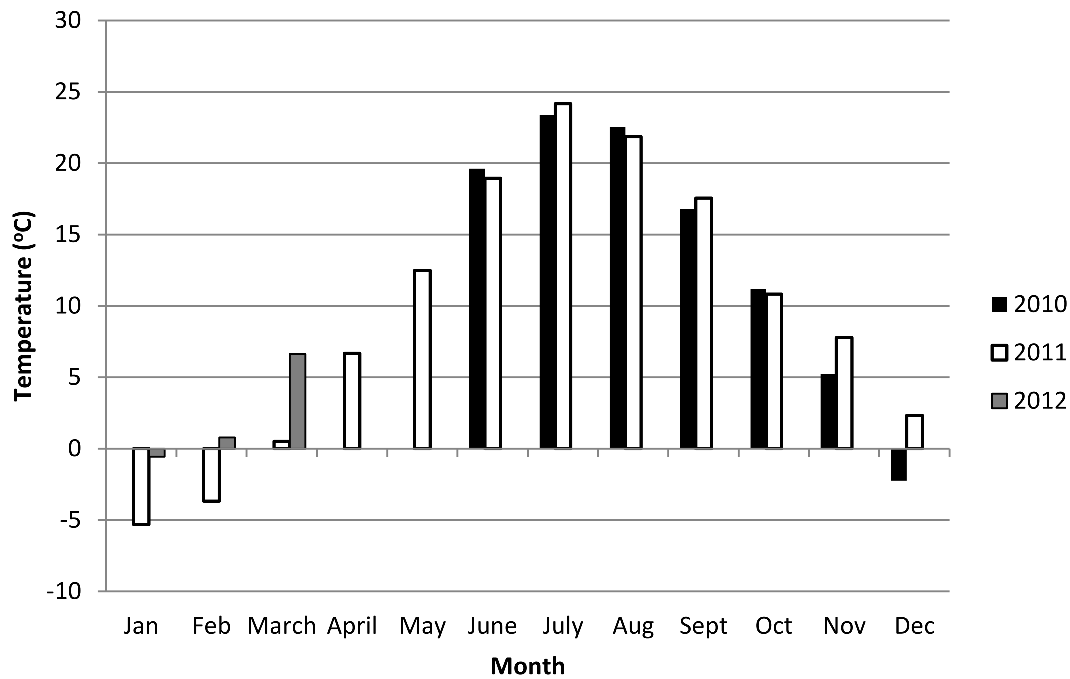


Figure A19 Mean monthly temperatures at Vineland Research Station for June to December 2010 (black), January to December 2011 (white), and January to March, 2012 (grey).

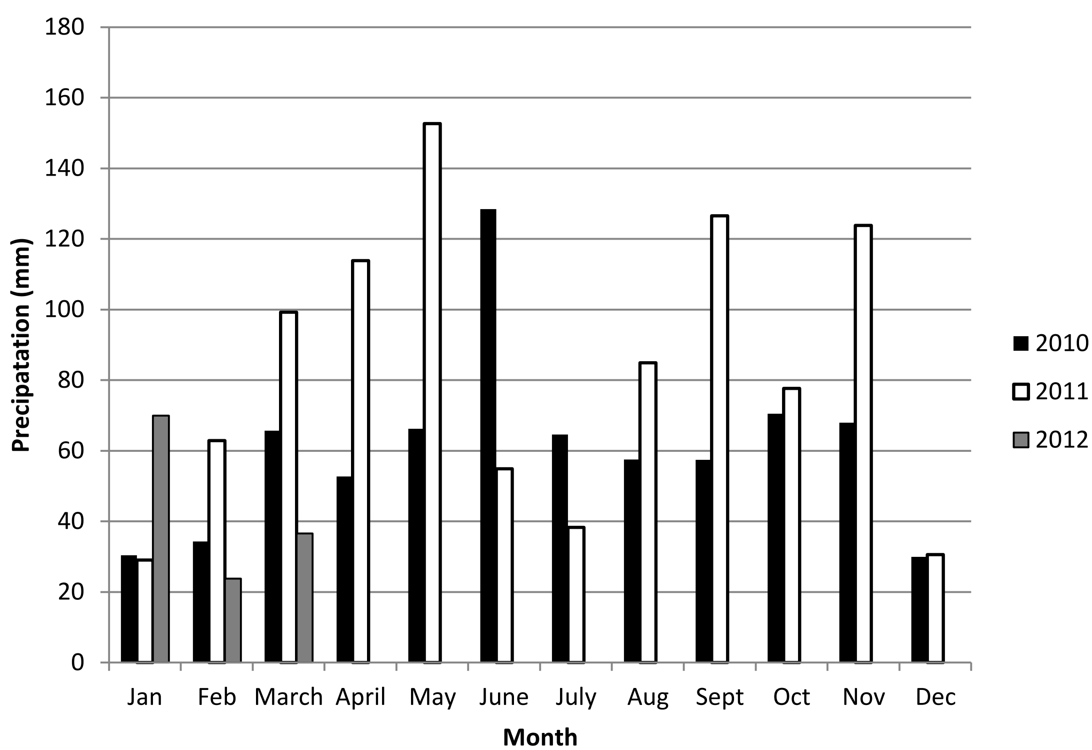
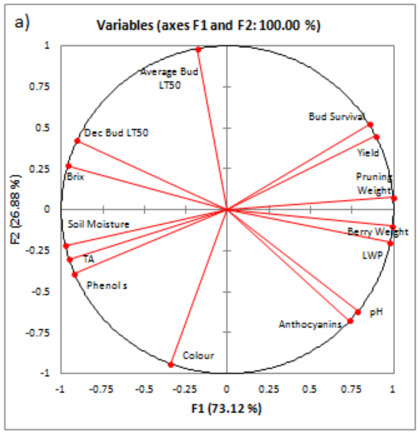
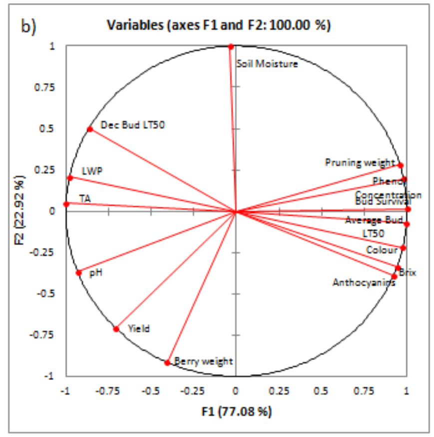


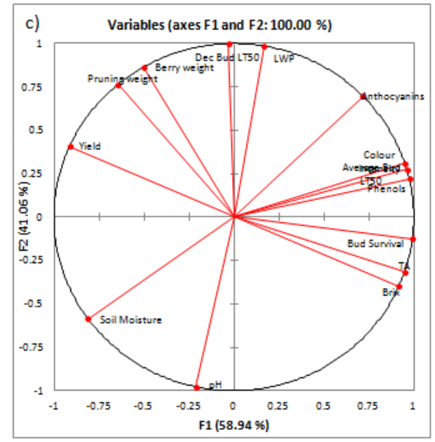
Figure A20 Mean monthly precipitation at Vineland Research Station for January to December 2010 (black), January to December 2011 (white), and January to March, 2012 (grey)



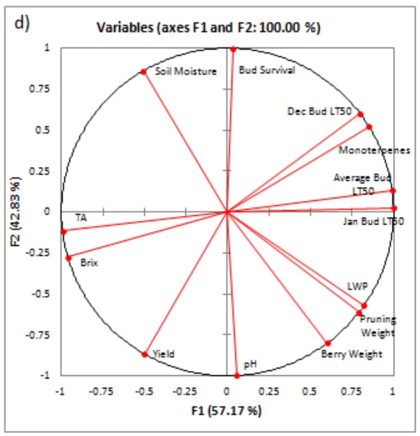
Dec Bud LT50 (Celsius) = -36.45 - 4.11*(berry weight) + 2.18*(TA) - 0.43*(LWP) + 4.71E-3*(pruning weight)

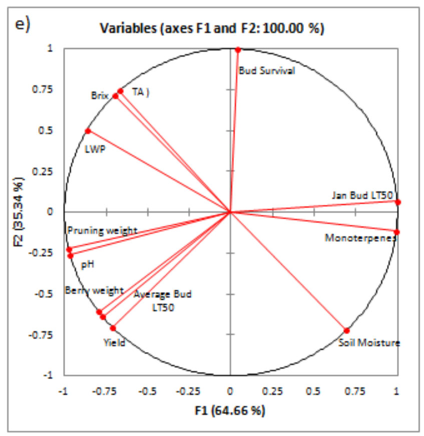


Dec Bud LT50 (Celsius) = -48.73 + 6.50*(pH) + 4.71E-3*(anthocyanins) - 1.18E-3*(phenols) + 0.36*(soil moisture)



Dec Bud LT50 (Celsius) = -33.00 + 0.93*(yield) + 0.01*(anthocyanins) - 2.56E-3*(pruning weight)





Jan Bud LT50 (Celsius) = -11.69 - 6.02*(berry weight) - 7.82*(pH) + 2.03*(TA) + 0.51*(monoterpenes) - 0.04*(bud survival) + 1.44E-2*(pruning weight)

Figure A21 PCA and multilinear regression results for the blocks which showed monthly discrepancies with mean bud LT50 correlations (referred to as anomalies, Chapter 3 and Chapter 4). The PCA biplots are given, followed by the linear regression equation below. No equation is given for Hughes 2010, as December Bud LT50 was found to positively relate to mean bud LT50. The figures are as follows: a) Kocsis Cabernet franc 2010, b) George Cabernet franc 2011, c) Lowrey Cabernet franc 2011, d) Hughes Riesling 2010, and e) Hughes Riesling 2011. A PCA was not completed for George Riesling. Its multilinear regression equation was Dec Bud LT50 (Celsius) = -20.65 – 0.29*(Brix) + 3.80*(pH) – 0.74*(TA).

Figure A22 Map of the Niagara wine region. Red circles represent Cabernet franc research blocks, green circles represent Riesling research blocks, and "+" represents the Vineland Research weather station. From left to right, Cabernet franc blocks are Cave Spring, Kocsis, George, Buis, Lambert, Lowrey; from left to right, Riesling blocks are Cave Spring, Hughes, George, Lambert, Buis, and Lowrey. Map courtesy of the Vintners Quality Alliance (VQA).